Metal/loids at New Great Consols

Report prepared for the Tamara Landscape Partnership

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1 Introduction

The Tamara Landscape Partnership is a five-year project [1] that seeks to improve health and wellbeing, opportunities for businesses and communities, environmental quality and maintain cultural and historic heritage. This report supports the aim of improving the water quality within the Tamar catchment. In partnership with the Environment Agency the initial focus for remedial interventions is on Luckett Stream, which fails environmental quality standards as a result of metal contamination, specifically copper, arising from historic mining in the catchment.

The scope of this report may best be considered in the context of the remediation workflow at contaminated sites (Figure 1-1): site investigations include the contextualisation of the mining legacy at Luckett (Section 2), a review of archive data (Section 3) and an evaluation of environmental trends and status of the New Great Consols mine site from the analysis of recent and new data (Section 4). Section 5 provides background information to remediation techniques, with detailed reference to Nature-Based Solutions (NBS) and Green and Sustainable Remediation interventions. Finally, Section 6 sets the aims for mitigation of site-specific sources and pathways at New Great Consols and evaluates the suitability of a range of interventions based on current research outlined in Section 5.

It is intended for this report to provide a range of options that enables the Tamara Landscape Partnership to make informed choices for interventions, for which the detailed design will be made in collaborations with third parties, who also facilitate the implementation, operation and evaluation monitoring.

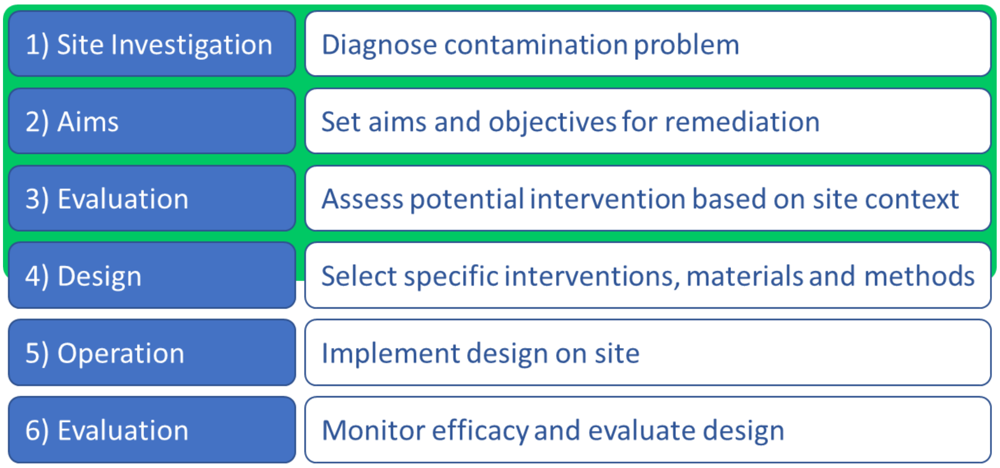

Figure 1-1 Workflow of remediation interventions for contaminated sites. The stages underlain in green represent those included in this report.

2 General Setting

2.1 Aims and Scope

This section provides a very brief background to the mining industry in Cornwall and West Devon. The aim is to provide a general context, rather than a comprehensive account, which may be obtained from the diverse and authoritative literature referenced. A glossary of technical terminology is provided in Section 7.

2.2 Non-technical Summary

Owing to its geological history, Southwest England naturally features areas of rich mineralisation and as a result, the background levels of metals and metalloids (or semi-metals, such as arsenic) in soils, rivers, streams and their sediments are naturally higher than elsewhere in the UK. For example, according to the British Geological Survey (BGS), the average copper concentration in rural soils across the UK is 21 mg/kg Cu (milligrams per kilogram), while the average for the whole of the Tamar catchment is more than double that (45 mg/kg Cu) and reaches over 2600 mg/kg Cu in the mining area of the Tamar Valley. Average copper concentrations in the Tamar catchment upstream of the main mining area are around 2 µg/L Cu (micrograms per litre) dissolved in the water and 85 mg/kg Cu in the sediment, whereas these parameters are up to 60 and 680 times, respectively, higher in the mining area of Callington/Kit Hill/Gunnislake [2, 3].

The veins of ores were discovered thousands of years ago and have been mined since pre-Roman times. However, the technological advances and demands of the industrial revolution brought on the most intensive aera of metal and metalloid exploitation in Cornwall and West Devon. The large-scale extraction of ores newly exposed a wide range of minerals to air and water in deep underground mines and in the vast quantities of waste rock brought to the surface. Consequently, the minerals undergo chemical changes in the process of oxidation that release contamination into soils and water. In addition, contamination is also associated with the sites where the ores were processed in the past. As a result, some groundwater, streams and rivers carry a heavy load of contamination, which together with other pollution sources has consequences for the ecology [4].

The Luckett Stream catchment lies within the Calstock/Gunnislake/Tavistock mining district known for its rich deposits of copper, arsenic, lead, zinc and silver and New Great Consols was poly-metallic and mined for copper, iron, tin and arsenic. Even today, abandoned mine sites and buildings are highly contaminated with a range of elements, and the local stream fails the environmental quality standards established for the UK.

In a general assessment of pollution risk to water courses undertaken in collaboration with the Environment Agency, New Great Consols ranked in the highest risk category alongside other sites nearby, such as Devon Great Consols mine in West Devon [5].

2.3 Geology, Ore, Production and Waste

The mineral deposits exploited by metal mining in Cornwall and West Devon originated in mountain forming events in the Earth's distant past. During the early Permian period, around 400 - 270 million years ago, the Varsican orogeny caused magma intrusions into the sedimentary bedrock of the Southwest Peninsular, which formed the Cornubian batholith, which today is partially exposed as the granites of Exmoor, Dartmoor, Kit Hill, Bodmin Moor, St Austell, Cammenallis and Land's End (Figure 2-1), as well as the Isles of Scilly [6]. Associated with this major geological event was the formation of concentrated, mineralised hydrothermal fluids and vapours that led, with the cooling and contraction of the granite, to the deposition of metal/loid ores in fissures and fractures [7]. Under the exclusion of oxygen, sulfide ores formed, with those of iron, copper, arsenic, lead, zinc and silver being particularly prevalent within the metamorphic aureole around the granites, the extent of which in the central Tamar catchment is indicated in Figure 2-2.

In the Southwest, ore discovery and metal mining commenced in the Bronze Age with the exploitation of alluvial tin (cassiterite) deposits close to the granite. Underground mining of lead and copper followed and initially was restricted in depth by gravitational dewatering of mines using adits and simple pump arrangements. Responding to technological advances and demand during the industrial revolution, the prime period for metal/loid production lasted from around 1700 into the late 19th century and declined in the early 20th century [8].

In an inventory of wastes associated with closed mines, the British Geological Society (BGS) identified two types of mineral deposits with potential environmental issues in the Southwest [9]:

i) major hazards connected to the granite-associated tin/copper fissure deposits (arsenic, antimony, copper, tin, iron, lead, zinc, cadmium and acid mine drainage or AMD) and
ii) moderate hazards connected to the Lower Palaeozoic shale-hosted lead-zinc deposits (lead, zinc, cadmium and AMD).

The main minerals present in SW England include cassiterite (tin, Sn), chalcopyrite (copper, Cu), arsenopyrite (arsenic, As), galena (lead, Pb), sphalerite (zinc, Zn and cadmium, Cd), wolframite (tungsten, W) and pyrite (iron, Fe). Other minerals of the same elements, as well as trace or minor minerals bearing fluor (F), uranium (U), silver (Ag), gold (Au), antimony (Sb), bismuth (Bi) and nickel (Ni) also occur.

This mineralogical diversity leads to much complexity and heterogeneity within the mined rock, extracted ore and waste materials associated with mines and ore processing facilities. As an illustration of the extent of waste associated with the production of 2 million tonnes (Mt) tin, 2.5 Mt copper and 0.25 Mt arsenic trioxide in the Southwest were an estimated 50 to 75 Mt of extracted rock and ground-up waste materials that cover an area of around 1500 to 2000 hectares today. The estimates for lead production and waste in this region are one order of magnitude below that in all three metrics [9]. In the Tamar Valley, metal ores vary widely in yield, from a few ounces of silver per tonne of material, to copper ore of 2% to 8.5% purity and lead ores of 50% to 70% purity [10].

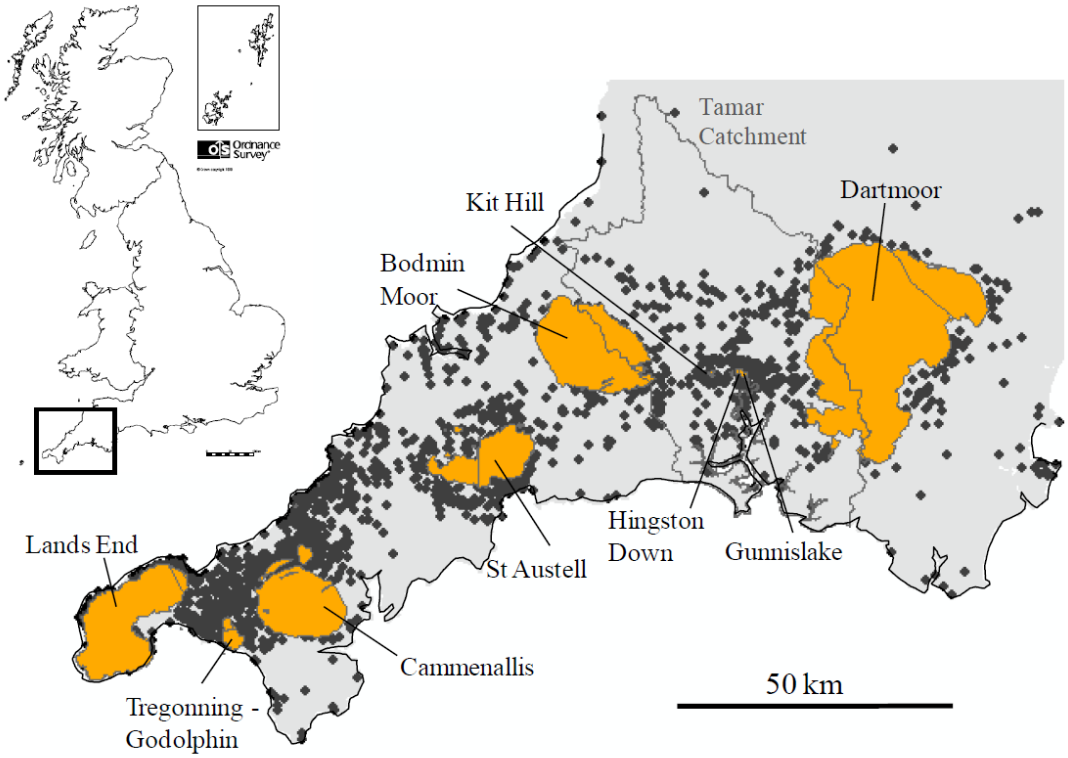

Figure 2-1 Location of metal/loid mines (black dots, data provided by [11]) in Cornwall and West Devon, with granite bosses (or intrusions) overlaid. Within the Tamar catchment (grey outline) the lesser intrusions of Kit Hill, Hingston Down and Gunnislake are associated with the area of most intense mining in the river valley. Reproduced with kind permission from [5] (Figure 1.4). Map base © Crown copyright and database rights 2023 Ordnance Survey 100049047.

A brief consideration of the methods involved in mining and processing of ore and the evolution of technology over time aids understanding the heterogenic characteristics of the waste materials and their potential environmental hazards. Large quantities of gangue have to be removed to reach and follow mineral veins, or lodes, whether in underground or open pit extraction. At the surface, gangue is dumped on waste piles nearby, while the desired metal/loid ore has to be broken out of ore-bearing gangue brought to the processing facilities in a size range that can be handled with the technology at the time. Ore-bearing rock is broken into smaller pieces to remove more of the gangue, the remainder ground and finally the ore separated for further processing. This process results in relatively free-draining waste dumps containing a mixture of coarse unmineralized rock, material bearing ores of no commercial interest at the time of processing (so-called guest metals), as well as varying amounts of the desired ore as a result of poor recovery.

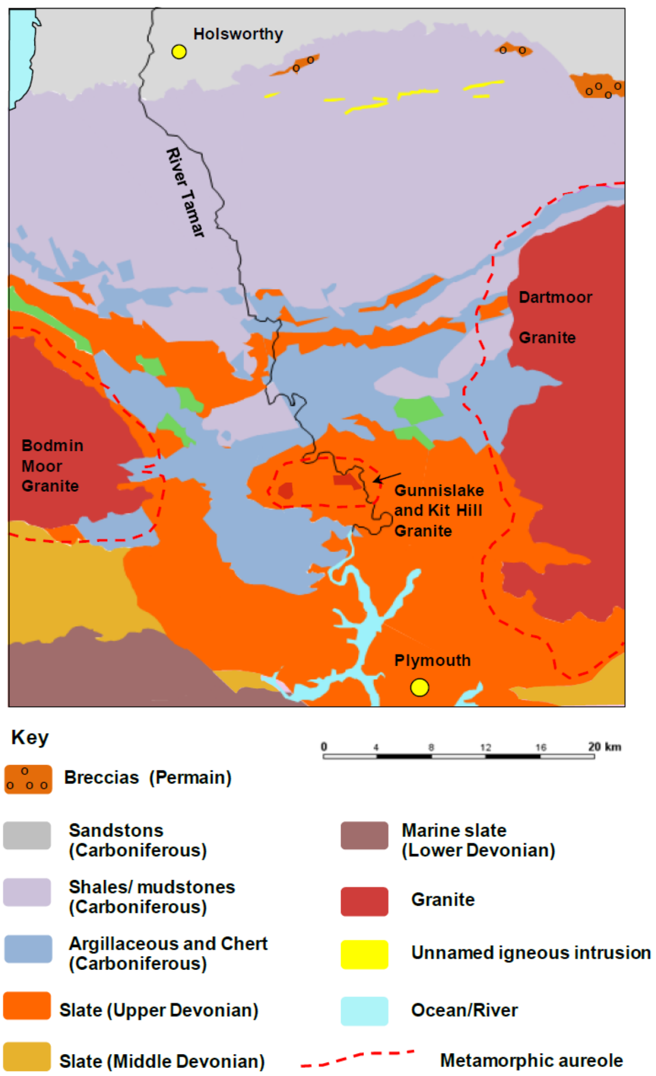

Figure 2-2 Geological map the area of interest within the Tamar catchment. Reproduced with kind permission from [12] (Figure 2.3). Geological Map Data © NERC 2008. Map base © Crown copyright and database rights 2023 Ordnance Survey 100049047.

Advances in mechanical crushing, grinding and hydraulic separation of the ore from the waste enhanced the efficiency of ore extraction over time, but also resulted in less permeable waste material dumps of material that has, collectively, a larger surface area. Within these dumps and tailings dams, the large surface areas of small grains are exposed to oxygen and water, so that sulfide minerals, such as pyrite, oxidise over time and act as source for metals (e.g. Cu, Zn, Cd, Pb, Ni, Fe), metalloids (e.g. As, Sb) and acid mine drainage (AMD) [9]. Re-processing of older waste dumps has been a wide-spread means to recover more of the originally mined ore or extract guest metals that have gained economic value since originally dumped. More advanced techniques, including finer grinding and more sophisticated hydraulic separation techniques added to the diversity of tailings deposits at such sites. In addition, smelting and calcination processes undertaken at various sites created yet again different types of waste material. At some mine sites, concentrated ore was shipped elsewhere for metal extraction adding to site complexity.

2.4 Mining in the Tamar Catchment - Overview

The Tamar catchment covers an area of approximately 1800 km^2 of West Devon and East Cornwall. The river flows for over 80 km from southeast of Bude on the Atlantic coast via its freshwater limit at Gunnislake weir into the English Channel (Figure 2-1) at Plymouth Sound. The catchment has been described as fairly responsive to rain events [13], a result of the low permeability and porosity of its geology (Figure 2-2) that limits the groundwater flow and storage. With a base flow index (BFI) of 0.47 approximately 30 km inland, in the region of Luckett, the rivers tend to spate flows following heavy rain events. The Tamar River has an annual average flow rate of 30 $m^3 s^{-1}$ with seasonal fluctuations from 5 to 100 $m^3 s^{-1}$. Land use in the catchment is predominantly agricultural (46% pasture, 36% forestry, 10% rough grazing, 7% arable) [13].

While Cornwall is widely renown for tin mining, within the Tamar valley tin is not dominant, as its occurrence is mainly associated with the granites on the catchment's margins. Instead, the most important area of mineralisation in the catchment is famous for its sulfide ores, in particular chalcopyrite (copper), arsenopyrite (arsenic) and pyrite (iron), although lead, zinc, silver and tungsten, amongst others, were also extracted in economically viable amounts. This is the Callington and Tavistock district, an area stretching 12 miles east to west and around 4 miles north to south between the edge of the Dartmoor granite and the metamorphic aureole (Figure 2-2) of the Gunnislake and Kit Hill granites [10]. Luckett Stream is a minor tributary to the Tamar River north of Kit Hill (Figure 2-3). To the north, a band of manganese ores was exploited between the rivers Ottery and Inny in the west, across to the Thrushel and Lyd in the east. The Lynher and

Tiddy sub-catchments drain catchments of similar mineralisation and are connected with the Tamar in the lower estuary (Figure 2-3).

The British Geological Survey and Environment Agency (EA) surveyed the Tamar River catchment at the resolution of roughly 1 sample per 2 km^2 in the context of the G-BASE (Geochemical Baseline Survey of the Environment) project and research associated with Special Areas of Conservation (SAC) [2]. The survey included some 460-490 soil, stream water and sediment samples that were analysed for key geochemical parameters and a range of metal/loids.

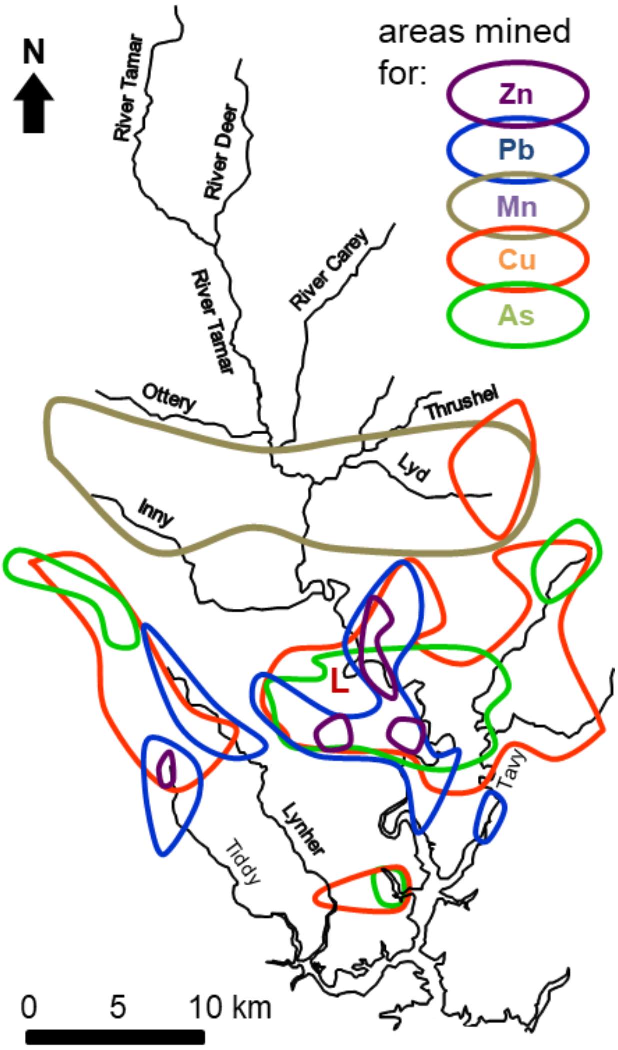

Figure 2-3 Approximate outlines of areas where zinc (purple), lead (blue), manganese (brown), copper (red) and arsenic (green) were mined in the Tamar River catchment. Luckett falls within the central, poly-metallic area (L). Based on data obtained from [11]. Adapted with permission from Figure 2.6 in [12].

Although the water quality in the catchment was generally very good in comparison to the EA's environmental quality standards (EQS) at the time (2003), elevated dissolved arsenic concentrations (5-33 µg/L As) and failures of the EQS for copper (6 µg/L Cu) around abandoned mine sites clearly showed their ongoing environmental impact. The river water EQS (50 µg/L As) for arsenic was not exceeded in the Tamar. In the report, Luckett Stream and its tributary at Downgate are among the water courses highlighted for arsenic concentrations between 15 and 20 µg/L (Figure 16 in [2]). Elevated copper concentrations were spatially correlated with high arsenic levels and reached up to 118 µg/L. In spot samples at isolated locations within the main mining district of the valley, cadmium, cobalt and nickel failed the drinking water guidelines and/or EQS for freshwater.

In stream sediments and soils within the Gunnislake/Callington mining district, concentrations of potentially toxic elements (PTE), including arsenic, copper, lead, tantalum, tin, tungsten and zinc were well above the typical soil concentrations of the Southwest outside mining areas [2]. The report deemed this particularly significant in times of high sediment load in streams during flood events, with potential effects on the ecology of the Tamar estuary and Plymouth Sound. Indeed, the environmental degradation of the Tamar estuary as a consequence of past mining activities has been well documented [14], in particular related to the sediment, with important impacts on the estuarine food web. Furthermore, outcomes of the PREDICT Tamar Workshop indicate that mining-related metal contamination contributes to toxic responses and DNA damage in organisms within the Tamar estuary, as do other stress factors, such as polyaromatic hydrocarbons related to traffic and agrochemicals [15-18].

Table 2-1 Range, average and median concentrations of metal/loids in rural soils in the UK [3] and the Tamar Catchment [2], compared with the range and median of available archive data at New Great Consols Mine, Luckett. EF is the calculated enrichment factor at NGC with respect to the mean for the United Kingdom.

Element	United Kingdom (n=366)				Tamar Catchment (n=468)				EF UK
(mg/kg)	min	max	mean	median	min	max	mean	median	mean
As	0.50	143	11	7.1	6.8	15000	79.1	22.9	7.3
Cu	2.3	97	21	17	2	2655	45	30	2.2
Mn	10	12200	612	420	77	33300	2300	1550	3.8
Pb	2.6	7.1	53	37	14	532	49	36	0.9
Sn	2.0	115	3.91	2	2	610	14	5	3.7
Zn	2.6	442	81	66	128	575	235	229	2.9

To place soil metal/loid concentrations of the Tamar Catchment and mining district into the wider UK context, summary statistics for rural soils of the UK [3] are compared in Table 2-1 with soil data reported by the British Geological Survey G-Base survey of 468 samples taken in the Tamar Catchment [19]. Concentrations in latter exceeded the UK average by factors of 7.3 for arsenic and between 2.2 and 3.8 for copper, manganese, tin and zinc. As soils are the product of bedrock weathering and biological processes, the elevated metal/loid levels in soils in this area are largely the result of the geological setting in the Southwest, with maximum concentrations occurring around historic mine sites.

According to the G-BASE survey, throughout the Tamar freshwater catchment, around 60% of soil samples exceeded the Soil Guideline Value for residential land use (SGV_R 20 mg/kg) at the time (2003) [19]. Taking the bioaccessibility of arsenic (around 20%) into account, the authors concluded that the area featuring a high probability (0.6 – 1) of residents being exposed to soils with potentially harmful arsenic concentrations (above 100 mg/kg As) comprised a relatively small area of the catchment, namely the area of intense mineralisation of in the Gunnislake/Callington mining district that includes the Luckett catchment (Figure 20 in [2]).

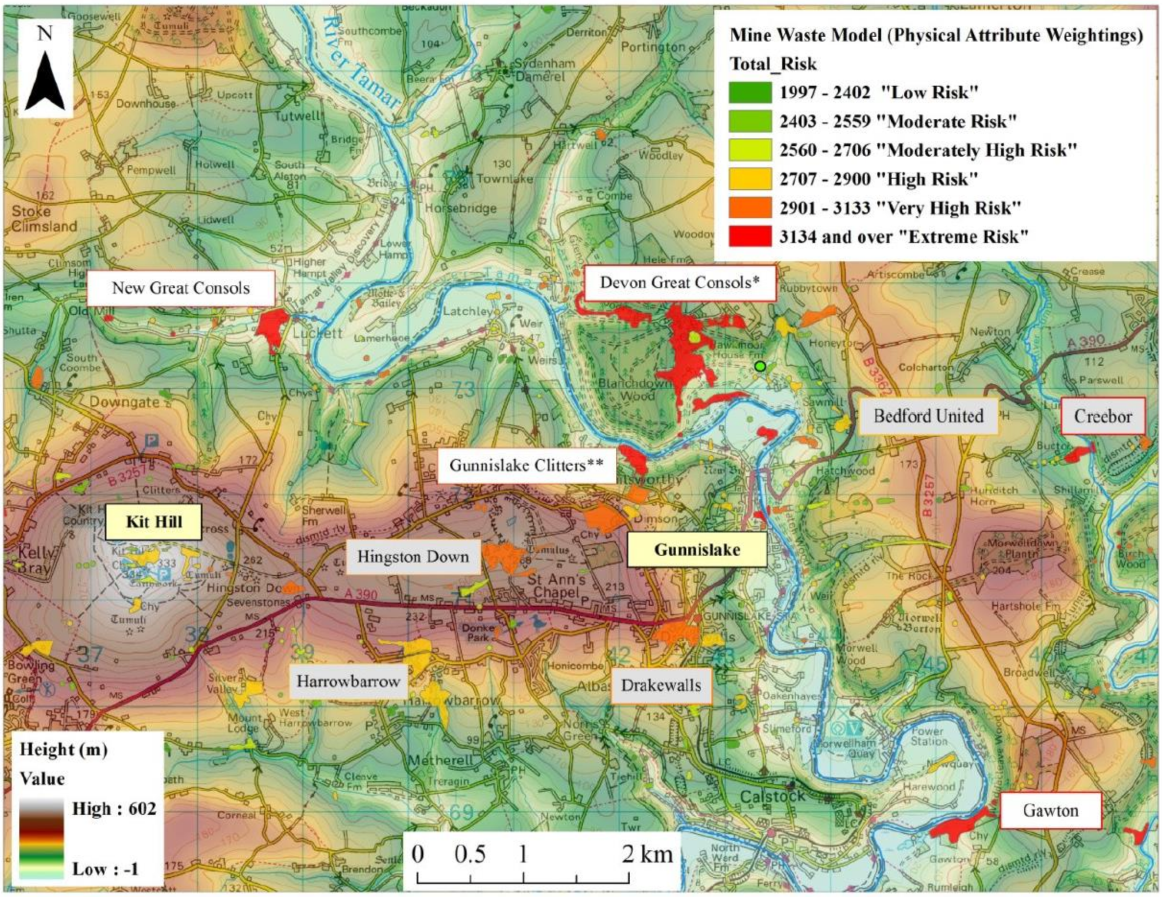

Figure 2-4 Mine waste risk model for the Gunnislake/Calstock/Tavistock mining district in the Tamar catchment. The model calculated the risk of diffuse pollution emanating from each known area of mine waste [11] on a scale from low to extreme risk on the basis of physical attributes explained in the text. Land altitude is shaded in to illustrate topography. Reproduced with kind permission from Figure 2.7 in [5]. Map base © Crown copyright and database rights 2023 Ordnance Survey 100049047.

In her environmental prioritisation of abandoned mine site of the Tamar catchment [5], Turner used a Geographical Information System (GIS) to create a multi-criteria decision analysis (MCDA) for the evaluation of environmental factors that influence the diffuse pollution output from mine waste tips to water courses. This included the proximity, topography, soils, bedrock and superficial geology, vegetation, wind speed, sun exposure, rainfall amount and intensity, each of which was categorised and weighted with respect to associated risk and incorporated into the GIS-MCDA model. This assessment did not take into account the contaminants and their concentrations at the sites. Instead, its purpose was to prioritise mine sites that purely on the basis of their physical characteristics, are problematic with respect to the potential export of any contamination present, and hence worthy of further investigation and remediation focus. The model output is summarised in Figure 2-4 and highlights a range of mine sites associated with 'extreme risk' to water courses, including the Devon Great Consols Mine, as well as Luckett, Gunnislake Clitters, and Gawton mines along the Tamar and Creebor mine in the Tavy sub-catchment [5].

2.5 Luckett New Great Consols and Associated Mines

The Luckett Stream catchment includes Stoke Climsland, Kelly Bray, Old Mill, Downgate, Hombush and Excelsior mines. The stream rises to the northwest of Kit Hill and flows in north-easterly direction to Old Mill, then through a wooded valley past Great Sheba Consols, Kelly Hole, Martha and New Great Consols mines and enters the Tamar River at Luckett (Figure 2-5) [11].

The history of *New Great Consols* (including *Martha*) is complex, with records indicating tin streaming activities in the 16th century and continuing into the post-medieval period [20]. The mine worked a number of poly-metallic lodes during the 18th and 19th century and the diversity of minerals [21] and potential impurities in the area presented a challenge to ore processing throughout the mine's history. Dines [10] provides records from the 18th century onwards, as summarised in Table 2-3, including reports of workings and outputs between 1764 and 1879, reworking of dumps during the first world war (1914 – 1918), and the reopening of the mine in 1946. The latter venture was doomed because of the complexity of ores and cost of working underground. '*Corrosive water*' in deeper levels of the mine formed an instant film of copper on all ironwork, and hot springs were encountered, from which sodium sulfate gas emanated [22]. The mine was closed in 1954 with a loss of recent investments. Further historic, technological and productivity details can be read in reference [23], who mentions three water wheels at the site, and black and white images of New Great Consols from the year 2000 are accessible at [24]. Further upstream in the valley, records cover outputs of *Great Sheba Consols* and *Kelly Hole* for the time between 1854 and 1864 [10].

Downgate, *Tom* and *Holmbush* were part of *Callington United*, which also included *Kelly Bray* and *Redmoor* mines outside or marginal to the Luckett catchment. *Kelly Bray* mines are connected with *Holmbush* at adit level, but apparently not below, and some leachate and drainage from its poly-metallic ores (Cu, As, Sn, Pb, Fe, W, Ag), workings and dumps of *Kelly Bray* may reach the Luckett catchment. *Holmbush* features a complex set of workings with five shafts connected by levels, crosscuts and lodes worked for a range of metals, including Pb, As, Cu, W and Ag. *Holmbush* is mentioned in deeds of the 17th century, but records only cover outputs between 1822 and 1886. For *Downgate* lodes containing arsenopyrite and tungsten were worked between 1914 and 1919, but the grade of ores was patchy [10].

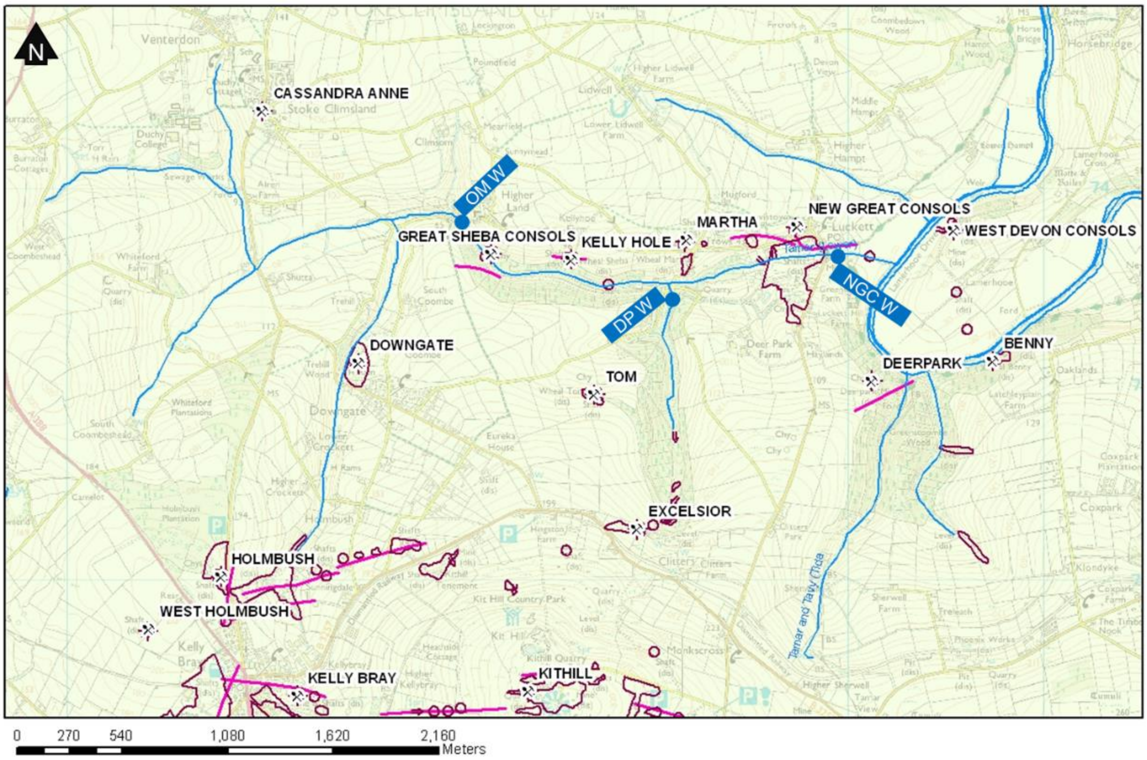

Figure 2-5 Mining features in the Luckett catchment. Crossed hammers: workings and shafts, dark red outlines: extent of surface features (remains of buildings, mine waste dumps etc.), purple lines: mineral veins or lodes. Reproduced with kind permission from [5]. Data © Environment Agency. Sampling stations added by the author for purposes of this report. Map base © Crown copyright and database rights 2023 Ordnance Survey 100049047.

Table 2-2 Main minerals worked and encountered at New Great Consols, Wheal Sheba and Broadgate mines. In addition, aluminosilicates, chlorite group minerals and tourmaline are listed for these mines. Common impurities are for listed minerals in general, hence should be seen as potential contamination, rather than specific to the localities around Luckett. Data collated from [21].

Mineral Name	Chemical Formula	Common Impurities
Arsenopyrite	FeAsS	Ag, Au, Co, Sn, Ni, Sb, Bi, Cu, Pb
Beryl	$Be_2Al_2(Si_6O_{18})$	Fe, Mn, Mg, Ca, Cr, Na, Li, Cs, O, H, OH, H_2O, K, Rb
Cassiterite	SnO_2	Fe, Ta, Nb, Zn, W, Mn, Sc, Ge, In, Sc, Ga
Chalcopyrite	$CuFeS_2$	Ag, Au, In, Tl, Se, Te
Fluorite	CaF_2	Y, Ce, Si, Al, Fe, Mg, Eu, Sm, O
Galena	PbS	Ag, Cu, Fe, Bi
Hematite	Fe_2O_3	Ti, Al, Mn, H_2O
Löllingite	$FeAs_2$	Bi
Pyrite	FeS_2	Ni, Co, As, Cu, Zn, Ag, Au, Tl, Se, V
Quartz	SiO_2	H, Al, Li, Fe, Ti, Na, Mg, Ge (and others)
Siderite	$FeCO_3$	Mn, Mg, Ca, Zn, Co
Sphalerite	ZnS	Mn, Cd, Hg, In, Tl, Ga, Ge, Sb, Sn, Pb, Ag, Co
Sulfur	S_8	Se, Te
Wolframite Group	$FeWO_4$, $MnWO_4$ (and others)	Nb, Ta, Sc, Sn (and others)

The remains of *Excelsior* lie within the wooded valley extending north of the Kit Hill foothills, and the mine recorded a small output of surface workings for tin between 1873 and 1884, but no output during later workings of the mine in the 1950s. *Excelsior Tunnel* was driven into the Kit Hill granite between 1881 and 1938 for a distance of around 730 m. Neither for this mine, nor for *Tom*, which had two lodes carrying tin and copper, records of outputs exist in Dines [10].

The diversity of ores (Table 2-2) and multi-elemental output (Table 2-3) of the mines in the Luckett catchment point towards a complex geochemistry, not only within the geology and underground workings, but also of the waste dumps and potentially contaminated remains of buildings on site today. There is some evidence that ores from nearby mines were processed at New Great Consols and that Luckett received quantities of waste materials from mine sites further afield, including Devon Great Consols, for reprocessing in the during the Second World War [25].

Table 2-3 Records of mine workings and outputs in the catchment of Luckett Stream. Common ores in the region are galena for lead (Pb), arsenopyrite for arsenic (As), chalcopyrite for copper (Cu), cassiterite for tin (Sn), wolframite for tungsten (W), sphalerite for zinc and cadmium (Zn, Cd), pyrite, siderite and haematite for iron (Fe), but other ores and native gold (Au) also occur. Data compiled from [10].

Name of Mine	Alternative Names	Shafts	Workings	Waste Dumps	Output	Reworked Dumps
New Great Consols, including Martha	Great Wheal Martha, New Wheal Martha, New Consols	5	Levels to 176 m, stoping	quarz, haematite, chalcopyrite, arsenopyrite, pyrite, tungsten	18.2 Mt Cu ore, 53 t Ag-bearing Cu precipitate, 1.3 Mt pyrite, 10.6 Mt Sn ore, 2.5 Mt arsenopyrite, 3.6 t As concentrate 'some' Au	180 t tin ore, 500 t As concentrate
Great Sheba Consols, including Kelly Hole	Trehill, West Wheal Martha	3	Levels to 110 m, crosscourses, stopes	quarz, chalcopyrite, arsenopyrite, pyrite, sphalerite, galena	5044 t Cu ore	
Downgate	none	none	level along lode, one crosscut	no records	10 t W ore, 4 t tin ore	
Holmbush, including West Holmbush	Flopjack, Lead Lode, Lady Beam	6	Levels to 320 m, stoping, crosscuts	galena, fluorspar, siderite,	43 Mt Cu ore, 20.3 Mt arsenopyrite, 10.6 Mt As, 1.7 t Pb ore, 3 Mt W, 108 t fluorspar 20,093 oz Ag	
Tom	none	2	no records	no records	Sn, Cu with no records of tonnage	
Excelsior	none	1	surface, levels along adits and lodes, no depth recorded	no records	5 t Sn ore	

2.6 Designations, Classifications and Landcover

Luckett New Consols Mine is a Scheduled Monument (No 1409595, National Grid Reference SX3869473462, SX3872573795) recorded with Historic England for 'Surface, buried and underground remains at New Consols Mine complex at Luckett, to the north and south of the main unclassified road which runs east to west through Luckett, Cornwall' [20]. The official entry provides details on the mining-related structures on the site today, including two beam engine houses and remains of a third, three shafts, adit portals, remains of an arsenic grinder house and chimney, remains of arsenic and tin calciners, arsenic flues, as well as remains of 20th century processing facilities, leats, culverts and an ore tramway.

The relatively level areas either side of the stream were dressing floors and are now extensive mining waste dumps, and records mention that the main adit of the mine is located within the stone-built culvert section of the stream. However, investigations carried out in 2021 by the Environment Agency did not detect an adit within the culvert.

The valley between Old Mill and Luckett and the valley leading to Excelsior are included in the Tamar Valley and Tavistock site of the World Heritage Site 'Cornwall and West Devon Mining Landscape', which acknowledges the cultural and archaeological legacy of thousands of abandoned metal mines in the region [26].

The UK Government online mapping service MAGIC [27] show:

- the village of Luckett and its catchment upstream to Old Mill is included in the Tamar Valley National Landscape (formerly Area of Outstanding Natural Beauty, AONB),
- the New Great Consols mine site features Priority Habitat Inventory Deciduous Woodland and other habitats of grassland, bog and dwarf shrub heath,
- the Groundwater Vulnerability Map classifies the catchment as 'medium - high' risk near the water courses of Luckett Stream and Tamar River and 'high' risk in the surrounding landscape.

3 Luckett Catchment - Archive Data

3.1 Aims and Scope

This section reviews data collected in Luckett Valley in the early 2000s and provides a basis for comparison of the environmental status with that a decade later, with the aim to identify any changes and trends in contamination and other parameters in later sections of this report. The information sources include unpublished work by undergraduate and postgraduate students of Chemistry, Environmental Science and Environmental Consultancy, where data quality is of verifiable standard, as well as PhD theses. Copies of some dissertations and all PhD theses are held in the University of Plymouth archive.

3.2 Non-Technical Summary

During the time of the surveys reported in this section (2005-2016), mine waste and buildings at NGC were highly contaminated and were the potential source of arsenic, copper and other elements from:

- solid mine waste resulting from the dumping of materials after recovery of economically valued ores,
- the dissolution of toxic salt deposits (efflorescent salts) on ore processing facilities,
- the leaching of pollution from mine wastes and contaminated soils by rainwater and shallow groundwater, and run-off to Luckett stream.

As a result, water and sediment in Luckett Stream were contaminated to the extent of failing environmental quality standards and there is evidence that they were adversely affecting macroinvertebrate communities.

3.3 Maps and Images

Figure 3-1 provides the contemporary Ordnance Survey map of the northern part of New Great Consols (NGC) mine site, as well as the sampling locations and viewing angles of archive photographs shown in Figure 3-2 to Figure 3-5.

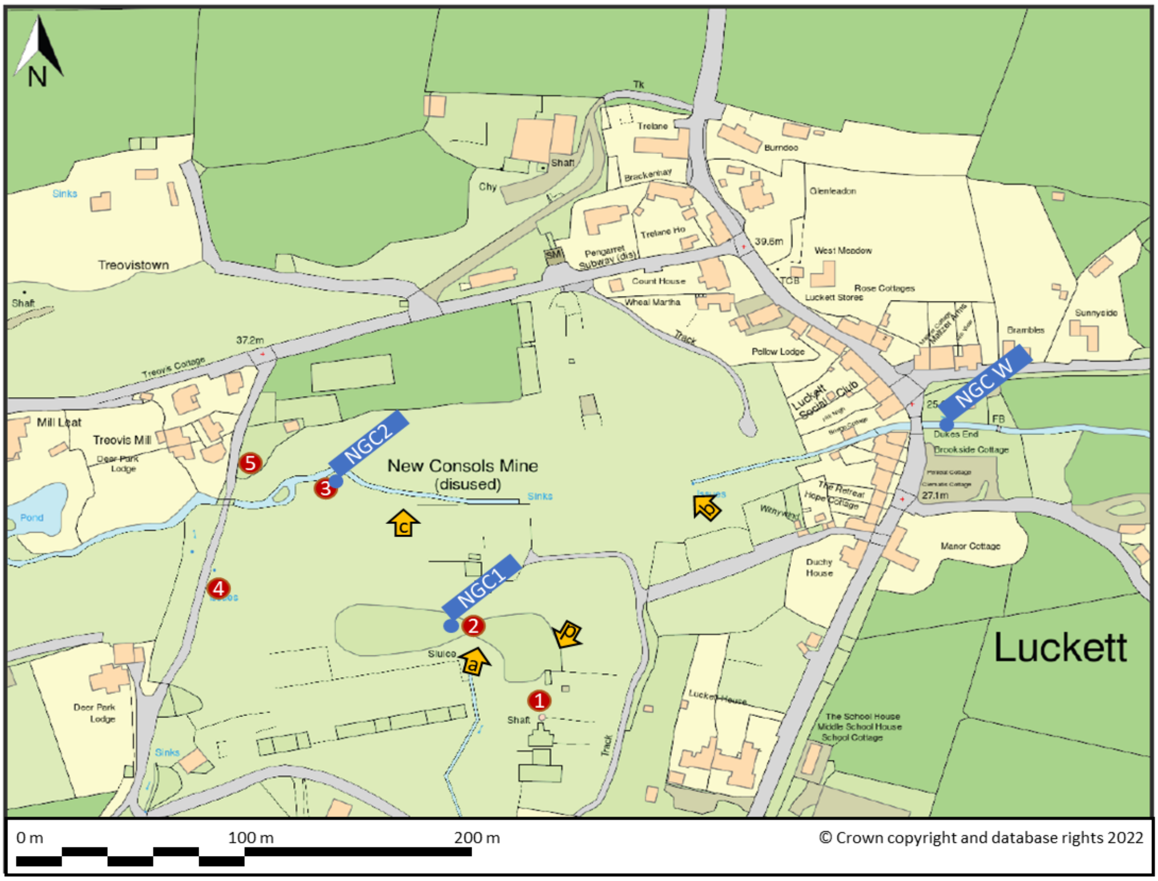

Figure 3-1 New Great Consols Mine site, with sampling sites (blue/red dots) and angles of photographs (yellow arrows) referred to in the following sections. Site Plan shows OSGridRef: SX38757351. Produced on 21st Dec 2022 from the Ordnance Survey National Geographic Database and incorporating surveyed revision available at this date. Supplied by mapserve.co.uk a licensed Ordnance Survey partner (100053143). Unique plan reference: #00785391-5DB0C6. Map base © Crown copyright and database rights 2023 Ordnance Survey 100049047.

Figure 3-2 Bottom left: Image taken at the sampling site sampling site NGC1 [12] and in proximity to Site 2 [28] on the map (Figure 3-1)). Right: view from above the waste dump where NGC1 was taken across the site towards the old engine house and village. Top left: remains of engine house near Site 1. Markers 'a' and 'd' relate to viewing angles of photographs indicated on the map. Photos: C Braungardt, 2005.

Figure 3-3 Photographs taken at sampling site NGC2 [12] and in proximity to Site 3 [28] on the map (Figure 3-1) on the occasion of preliminary water sampling and mine waste sampling for the project detailed in [12]. Photos: C Braungardt, 2005/6.

Figure 3-4 The exit of the culvert (left) within the site and run-off carrying a high load of suspended sediment from the waste dumps into Luckett stream. Yellow markers ‘b’ and ‘c’ relate to viewing angles indicated on the map (Figure 3-1). Photos: C Braungardt, 2006.

Figure 3-5 Image across the top of the row of calciners at New Great Consols (right, east to west) and the efflorescent precipitates on the inside of the structures, with typical whitish-grey cauliflower appearance of arsenic oxides and turquoise precipitates of, presumably, efflorescent copper minerals. Photos: C Braungardt 2005.

3.4 Mine Waste and Soils

Five samples of solids from mine waste dumps and soils at Luckett New Great Consols (NGC) were characterised by Melling-Flavell for their physico-chemical parameters and contaminant concentrations [28]. Sampling sites (1-5, Figure 3-1) were described in autumn 2005 as such:

- Site 1: Sheltered with vegetation including scree oak, beech, nettle, fern (bracken), hawthorn, blackberry and ivy, with leaf litter covering the area and lichens on rocks.
- Site 2: Very exposed with grey sandy substrate. No vegetation at sampling point, but gorse and heather within 5 m of the sample location.
- Site 3: Very exposed with clay-like spoil next to the stream. No vegetation, but birch, beech, gorse and heather within 5 to 6 m of the sample location.
- Site 4: On the edge of the mining area, a thin surface layer of brown soils covered grey clay substrate. Vegetation comprised of grass cover, oak, hawthorn, gorse, ferns (bracken), blackberry and a small amount of heather.
- Site 5: Off the mine site at the old mill house. Vegetation included grass cover and coniferous trees.

Mighanetara [12] collected two sub-surface (5 cm depth) samples in 2006 from mine waste dumps at Luckett, whereby sample locations NGC1 and NGC2 correspond closely to Melling-Flavell's Sites 2 and 3, respectively (shaded in corresponding colours in Table 3-1). NGC1/Site 2 were collected at the slope of a mine waste dump and both were characterised by very poorly sorted silty sand of moderately low pH (4.9-5.5, Table 3-1). NGC2/Site 3 were more finely grained white tailings that formed the bank of the stream. These tailings, as well as Melling-Flavell's samples from site 3 were of very low pH, especially at depth (pH1.8-2.8). Outside of the mining area, Site 5 featured more natural soils (pH6.0-6.3) [28]. Pseudo-total (*Aqua Regia*) metal/loid concentrations confirm the heterogeneity of the site. With the exception of tin (100-190 mg/kg Sn), the concentrations of metal/loids varied by one to three orders of magnitude between samples collected at the time (590-24000 mg/kg As, 76-850 mg/kg Cu, 7500-69000 mg/kg Fe, 91-1600 mg/kg Mn, 73-1000 mg/kg Pb, 16-490 mg/kg Zn, Table 3-1).

An evaluation of the potential mobility of contaminants has been made on the basis of the modified BCR sequential extraction method [29], which targets the easily mobilised (exchangeable), reducible and oxidisable fractions with increasingly aggressive sequential extraction protocols. Compared to the pseudo-total concentration extractable by hot *Aqua Regia*, the percentage of the potentially mobile fraction has been provided by [12], and is summarised here:

- The exchangeable fractions of As, Cu, Fe, Mn and Zn were in the region of or below 1% of the total concentrations.
- The overall mobility (exchangeable, reducible and oxidisable fractions combined) of As in the mine spoil heap (NGC1) was 36%, mainly attributed to reducible and oxidisable species. In contrast, the As mobility in the white tailings (NGC2) near the river was 1% of the total.
- The overall mobility of Fe was 20% of the total, and similarly to arsenic, the oxidisable fraction dominated.
- The overall mobility of Pb in NGC2 was 63%, mainly in exchangeable and oxidisable fractions, while in NGC1, lead mobility was negligible.
- Copper, Mn and Zn were predominantly present in residual forms, and these are not easily mobilised even if environmental conditions shift towards more reducing or oxidising conditions.

*Table 3-1 Physico-chemical characteristics and metal/loid concentrations at New Great Consols. 'NGC' samples by Mighanetara, 'EM, samples by Melling-Flavell (**s** and **d** denote surface and 30 cm depth samples). Total carbon (TC) determined with a CHNS analyser (EA1110, CE Instruments) and the loss of weight on ignition (LOI) after treatment of dried samples (105°C) at 440°C for 8 hours, both in % of the dry weight. Total metal concentrations were determined after hot acid extraction, either on the hot plate (KM,* Aqua Regia*) or by microwave digestion (EM, HNO_3). Values were rounded to two significant figures and standard errors were omitted for clarity. Ni and Cd were at concentrations close to the limit of detection (LOD) and omitted. 'nd.' means not determined. Data compiled from raw data generated by [12] and [28].*

Sample	NGC1	NGC2	EM1 s	EM1 d	EM2 s	EM2 d	EM3 s	EM3 d	EM4 s	EM4 d	EM5 s	EM5 d	Min.	Max.
pH	4.9	3.8	4.9	5.6	5.5	3.2	2.8	2.3	2.1	1.8	6	6.3	1.8	6.3
TC (% wt.)	<0.1	0.2	nd.	nd.	nd.	nd.	nd.	nd.	nd.	nd.	nd.	nd.	0.2	0.2
LOI (% wt.)	0.1	0.1	nd.	nd.	nd.	nd.	nd.	nd.	nd.	nd.	nd.	nd.	0.1	0.1
Gravel (%)	6	0	nd.	nd.	nd.	nd.	nd.	nd.	nd.	nd.	nd.	nd.	0	6
Sand (%)	50	42	9	13	54	52	8	15	4	9	19	23	4	54
Silt (%)	35	33	82	76	39	40	84	74	87	78	70	69	33	87
Clay (%)	9	25	9	11	7	8	8	11	9	13	11	8	7	25
AsT (mg/kg)	6400	12000	590	850	21000	24000	21000	11000	22000	14000	1300	1600	590	24000
CuT (mg/kg)	76	850	100	160	90	110	120	640	240	130	240	370	76	850
FeT (mg/kg)	7500	69000	39000	47000	17000	21000	42000	41000	33000	15000	46000	28000	7500	69000
MnT (mg/kg)	<LOD	91	1200	1400	<LOD	<LOD	200	260	<LOD	<LOD	1600	750	91	1600
PbT (mg/kg)	<LOD	360	73	100	190	230	490	1000	470	540	190	410	73	1000
SnT (mg/kg)	nd.	nd.	<LOD	<LOD	140	150	120	190	100	140	<LOD	<LOD	100	190
ZnT (mg/kg)	20	410	26	41	22	26	36	16	82	18	290	490	16	490

Mineralogical studies of the mine waste by QEMSCAM® analysis revealed contrasting constituents of the mine waste (Figure 3-6) [12, 30]. The waste heap sample NGC1 comprised of 54% quartz and 43% other silicate minerals, with 1.9% Fe-oxides or Fe-carbonates, 0.1% pyrite, 1.1% scorodite, 0.1% As phases other than scorodite and other primary ore minerals (e.g. sphalerite, chalcopyrite, galena) less than 0.1% each. This was in agreement with the relatively low metal content of NGC1, compared to NGC2 and other mining waste in the region [5, 12, 31]. It should be noted that scanning electron microscopy cannot identify hydrogen and therefore, particles identified as Fe-oxides are likely to be Fe-oxyhydroxides or Fe-hydroxysulfides resulting from oxidation of sulfide minerals and subsequent precipitation in acidic conditions. Acid mine drainage precipitates include, depending on the redox/pH conditions present, goethite, ferrihydrite, schwertmannite and jarosite, and in amorphous forms, have a large specific area and affinity for arsenic (both, As(III) and more so As(V)). Arsenic associated with the relatively mobile 'Fe-oxide/carbonate' phases identified in this sample could explain the high mobility of arsenic identified in the sequential extractions.

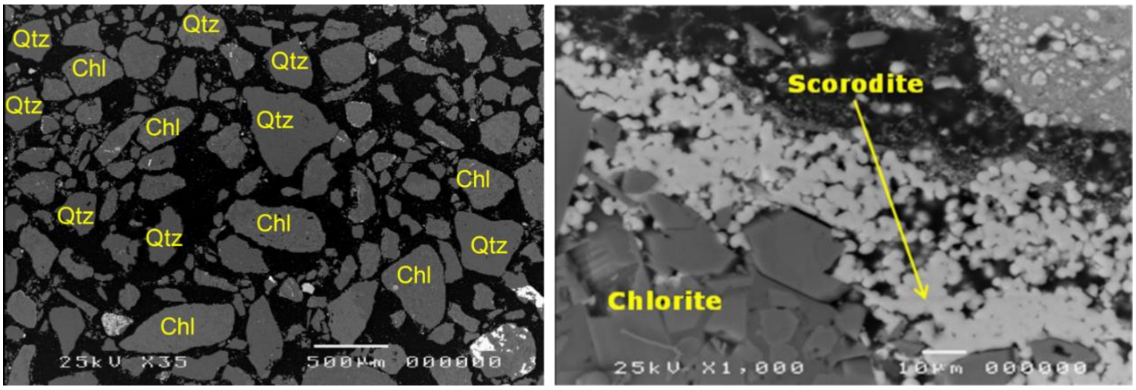

Figure 3-6 Backscattered scanning electron microscopy image of a subsample of NGC1 (left) and NGC2 (right). Quartz (Qtz) and chlorites (Chl) dominate NGC1, while NGC2 shows precipitation of scorodite on chlorite particles. The Fe-As-O phase identified as scorodite contained 45% O, 22% As and 20% Fe. Reproduced with kind permission from [12] Figures 4.13 and 4.14.

The tailings sample NGC2 had much lower quartz and silicate contents (32%) and was instead dominated by arsenic phases (64% scorodite, 0.4% arsenopyrite, 0.1% other), with low Fe oxides/carbonates (2.8%) [30]. The much higher metal concentrations, compared to NGC1, in this sample are corroborated by this distribution, although the analysis did not show significant amounts of Pb or Zn minerals. Scorodite ($FeAsO_4 \cdot H_2O$) is a relatively stable secondary mineral with low solubility and its abundance in NGC2 reduces the overall mobility of As in the sample. Although the Cu concentration in this sample was relatively high (850 mg/kg Table 3-1), chalcopyrite and other Cu phases each comprised less than 0.1% of the sample, which may be explained by the abundance of iron/arsenic phases and the fact that the total Fe concentration in the samples was 2 orders of magnitude higher than that of Cu.

The contamination of remaining buildings on sites, in which arsenic and tin calcination took place, is likely to be of concern as source of contamination to the wider environment. Efflorescent salts precipitate on porous surfaces, such as rock or brickwork, as a result of wetting and drying cycles, whereby fluids enriched in contaminants evaporate due to wind/sun/heat exposure, leaving behind 'blooms' of crystals. This occurs on natural surfaces and on mine waste dumps when water dissolves minerals within, as well as in buildings, in which mortar and brickwork is impregnated with minerals as a result of their former use in metal/loid processing.

At NGC, efflorescent blooms have been observed on the inside and apertures of calciner ruins (Figure 3-5) and the chimney built to disperse the labyrinth fumes in the south of the site. They are also likely to be present in the collapsed and overgrown remains of calciner flue gas chambers (labyrinths) and their flues and chimneys. Although no samples were analysed from the arsenic calciners at NGC, similar samples obtained from the outside walls of the labyrinth at Devon Great Consols mine across the valley contained 140 g/kg As, or 14% by weight, 75% of which was established as being in the exchangeable fraction (BCR sequential extraction protocol, [12]) and hence constitute a highly soluble form of arsenic oxide. The potential toxicity of efflorescent salts in these structures must be considered in risk assessments carried out for any contractors working on site (see Appendix in Section 9).

Outside the NGC envelope, five samples (at 10 cm, 60 cm and 80 cm depths each) of not recently cultivated soil were taken in autumn 2004 in a private garden adjacent to the site. The location was surrounded by woodland trees and covered in grasses, some herbs and shrubs. The soil profile featured a litter horizon and loamy root zone and showed no signs of underlying mining waste. Leaching of samples with artificial rain at pH 4 was undertaken to evaluate the potential for mobilisation and biologically uptake of potentially toxic elements from the soil. The results showed very low mobility of As (6.5 mg/kg), Cu (2.6 mg/kg), Pb and Sn (0.71 mg/kg) and Zn (2.1 mg/kg) under the experimental conditions (unpublished data, C Braungardt) and raised no contamination concerns with respect to developing an orchard on the site.

3.5 Water Quality

As part of a wider study into the export of contaminants from mine sites into the Tamar River [32], monthly samples were taken between July 2005 and June 2006 in Luckett Stream downstream of the NGC site at the public car park (NGC W) and in Deerpark stream (DP W, Figure 2-5).

During this period, the average flow rate of Luckett Stream at NGC W was 350 L/s (range 74-1000 L/s), with higher flow rates encountered between November and February (Figure 3-7). Sulfate concentrations (16±3.1 mg/L) did not exhibit a distinct seasonal variation, neither did the redox potential (Eh 260±70mV), conductivity (55±22 µS/cm) or pH (7.02±0.2). The metal/loids showed different partitioning patterns between the dissolved (filtered at 0.45 µm pore size) and particulate phases. While concentrations in both phases were similar for iron, in most samples, dissolved Cu, Zn and Mn dominated partitioning in the water column. Arsenic partitioning in some samples was alike that of Fe and in others more akin to Zn and Cu (Figure 3-7). Combined (dissolved + particulate) concentrations of Ni (mean 16±9.3 µg/L) and Co (9.4±4.8 µg/L) were relatively low, with some values below the limit of detection (LOD) of the analytical method used (LOD 0.5 µ/L Ni, 0.4 µg/L Co). Dissolved Pb was below the LOD of 0.4 µg/L Pb in all samples, but detectable in the particulate phase (mean 0.54±0.1 µg/L). Caesium (mean 0.81±0.3) was only detectable in the dissolved phase (LOD 0.17 µg/L Cs).

The average flow rate in Deerpark Stream (DP W), which drains a Kit Hill adit and Excelsior mine, was 43 L/s (range 9-110 L/s), lowest in September and highest in December. pH values (pH 6.78±0.2) were slightly lower than in Luckett Stream and the redox potential was higher (Eh 300±86 mV). Metal/loid concentrations at DP W were highly variable in the dissolved phase and largely below LOD in the particulate phase, largely because of very low suspended sediment loads. Compared to NGC W, average conductivity (26±16 µS/cm) and dissolved concentrations for sulfate (9.9±3.5 mg/L), Mn (14±7.5 µg/L), Cu (18±18 µg/L), Zn (22±15 µg/L) and As (12±1.8 µg/L) were lower than at NGC W by at least a factor of two and below LOD for Fe, indicating that for these parameters, Deerpark Stream presented a dilution, rather than a source to Luckett stream. The dissolved concentrations of Co, Ni and Cs were similar in the samples taken at DP W and NGC W.

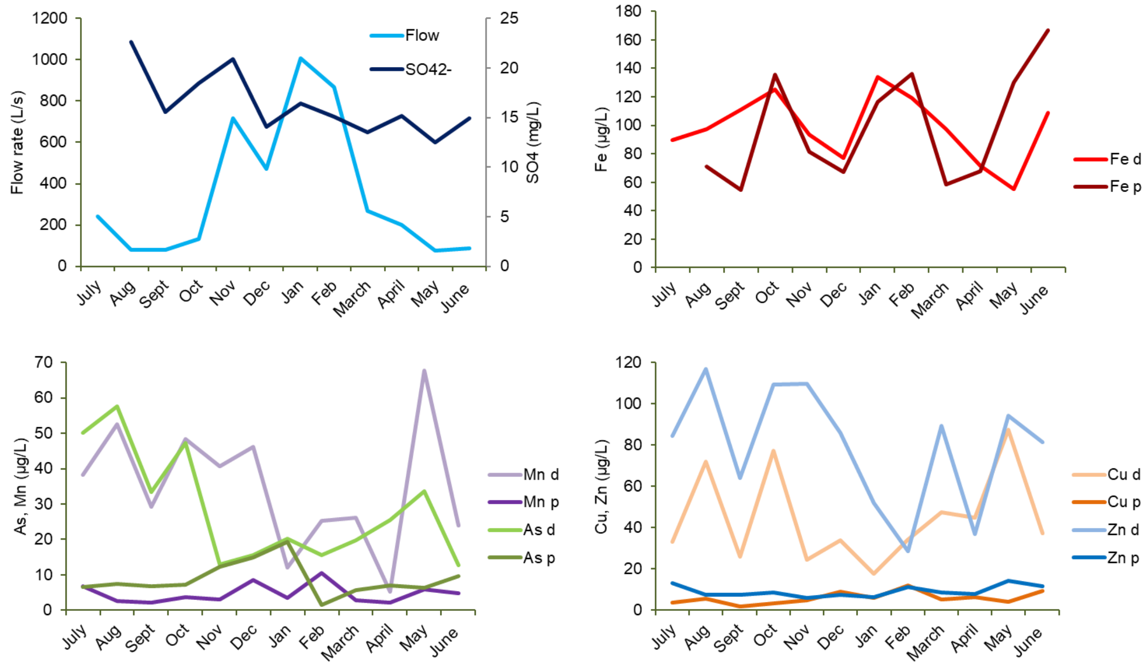

Figure 3-7 Flowrate, sulfate and metal concentrations in 12 water samples taken between July 2005 and June 2006 in Luckett Stream downstream of New Great Consols at the car park (NGC W, Figure 2-5) and road bridge. The legends refer to dissolved (d) and particulate (p) concentrations of iron, manganese, arsenic, copper and zinc, expressed in µg/L. Raw data provided by K. Mighanetara.

The authors of [32] calculated monthly and annual metal/loid fluxes by interpolating the instantaneous data obtained from monthly surveys, with the caveat that the assumptions made are not necessarily representative of the highly variable rainfall, stream flow and erosion or leaching patterns in the mining area. Nevertheless, the data may provide an indication of seasonal variability that could be useful in the context of considering the effectiveness of nature-based remediation options in different seasons.

Combined particulate and dissolved fluxes of Fe (annual total 2300 kg/a), Zn (870 kg/a), Cu (450 kg/a), Mn (390 kg/a) and As (360 kg/a) exhibited a distinctly seasonal pattern (Figure 3-8). Both, particulate and dissolved metal/loid fluxes covaried strongly with stream flow (Pearson's correlation coefficients between 0.75 and 0.98 at 99% confidence level). Of the calculated annual metal/loid fluxes, 46% Fe, 11% Zn, 18% Cu, 16% Mn and 33% As were present in the particulate phase. In the interest of comparing dimensions, the estimated the flux of metal/loids in the Tamar at Gunnislake were 425 t/a Fe, 12.7 t/a Zn, 15 t/a Cu, 80 t/a Mn and 5.4 t/a As, mainly from diffuse sources [32].

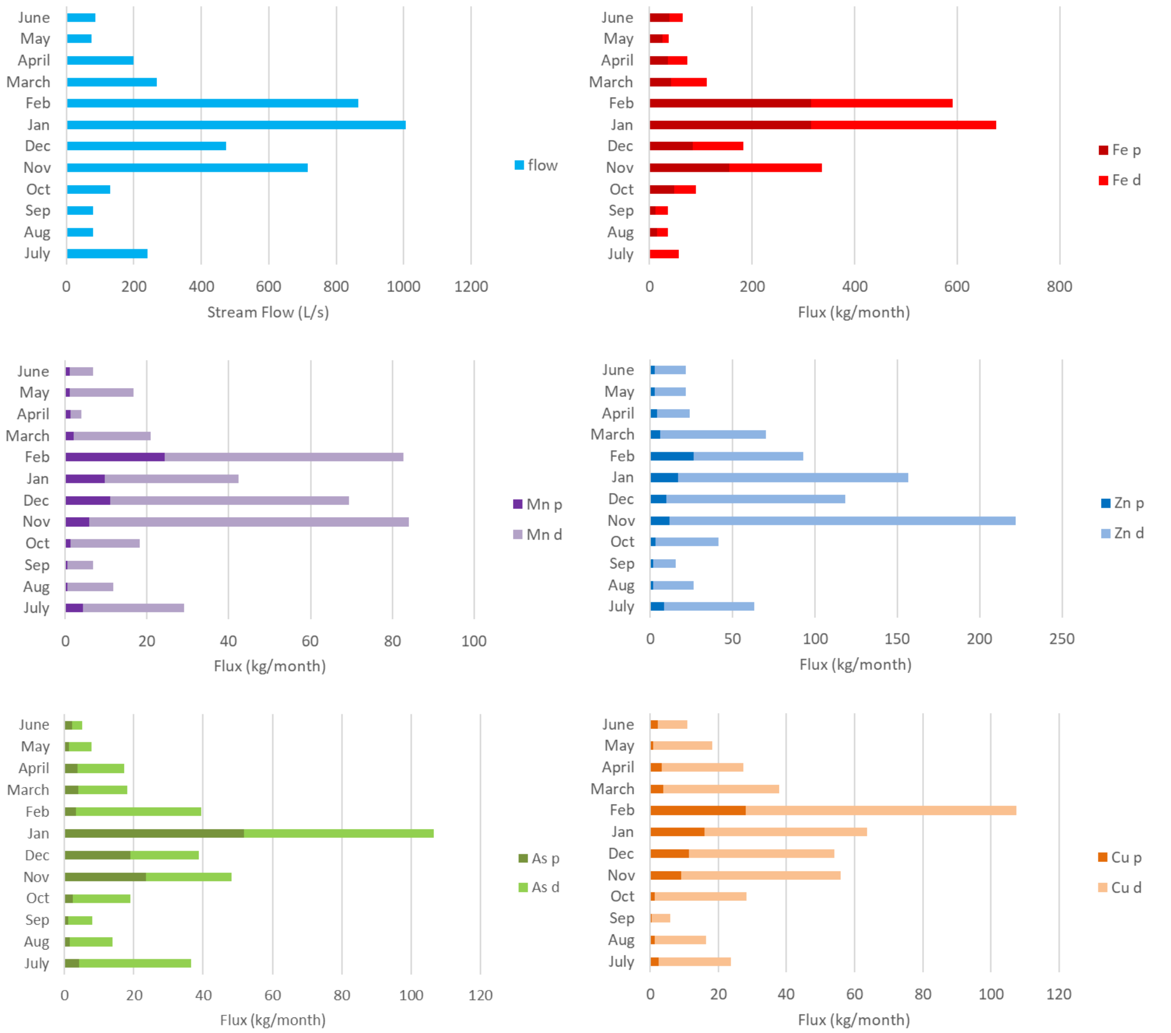

Figure 3-8 Metal/loid fluxes (or loadings) interpolated from monthly samples taken in Luckett Stream at NGC W (Figure 2-5) between June 2005 and 2006. The legends refer to dissolved (d) and particulate (p) fluxes of iron, manganese, arsenic, copper and zinc, expressed in kg/month. Raw data provided by K. Mighanetara.

Samples from Luckett stream were taken annually in October between 2008 and 2016, at Old Mill (OM W), Luckett car park (NGC W, Figure 2-5) and in Deerpark Stream (DP W) during field work of MSc Environmental Consultancy cohorts at the University of Plymouth. Most of the parameters determined in these samples were consistent with the range of values for the monthly surveys by Mighanetara during 2005/6 (Table 3-2). A notable exception was conductivity, which was on average around three times higher during the October surveys at both locations in Luckett Stream. Compared to the upper Tamar catchment, the average October concentrations of Zn and As were indicative of metal/loid mineralisation in the Luckett catchment upstream of Old Mill.

Table 3-2 Comparison of average water quality parameters of the October surveys and monthly samples taken by Mighanetara in 2005/6 in Luckett and Deerpark Streams (Figure 2-5). The ranges for the upper Tamar catchment north of Launceston include the Tamar, Deer, Carey and Ottery rivers as a regional background [32].

		October Surveys 2008-2016						Monthly Surveys 2005/6				Upper Tamar
		Old Mill		Deerpark		Luckett		Deerpark		Luckett		Catchment
Parameter	Units	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev	Range
Flow rate	L/s	420	210	70	17	590	140	37	33	350	330	
pH water		6.98	0.64	6.21	0.82	6.7	0.63	6.78	0.23	7.02	0.2	7.0-8.4
Conductivity	µS/cm	148	33	102	7.3	147	15	29	16	55	22	39-84
Redox potential	mV	440	66	420	72	400	190	320	85	260	70	310-700
Ca dissolved	mg/L	16	3.5	4.3	1.7	13	2.8	5.4	1	19	2.4	13-25
K dissolved	mg/L	3.1	1.1	1.1	0.058	2.1	0.38	1.1	0.24	2.4	0.5	2.8-5.1
Mg dissolved	mg/L	5.4	0.59	4.3	0.65	5.1	0.39	4	0.91	6.9	0.92	3.7-6.8
Na dissolved	mg/L	11	3.2	9.6	2.2	11	2.2	8.9	0.35	11	0.83	13-19
PO4-P	µg/L	84	43	2.2	1.9	47	29	n/d		n/d		
NO3-N	mg/L	5.1	0.63	3.2	0.35	4.2	0.94	n/d		n/d		
Mn dissolved	µg/L	38	9.3	3.5	2.3	22	0.92	12	7.5	36	20	2.1-120
Fe dissolved	µg/L	33	26	7.4	4.4	52	35	<LOD		98	23	60-390
Ni dissolved	µg/L	2.2	0.26	1.8	0.5	2.6	0.17	9.7	6.3	15	8.4	1.2-5.3
Cu dissolved	µg/L	4.3	2.5	0.76	0.46	13	6.0	18	18	45	22	7.6-17
Zn dissolved	µg/L	56	23	24	5.3	125	98	18	15	80	29	<6.4
As dissolved	µg/L	16	2.9	3.0	0.36	30	4.4	12	1.8	29	16	<12

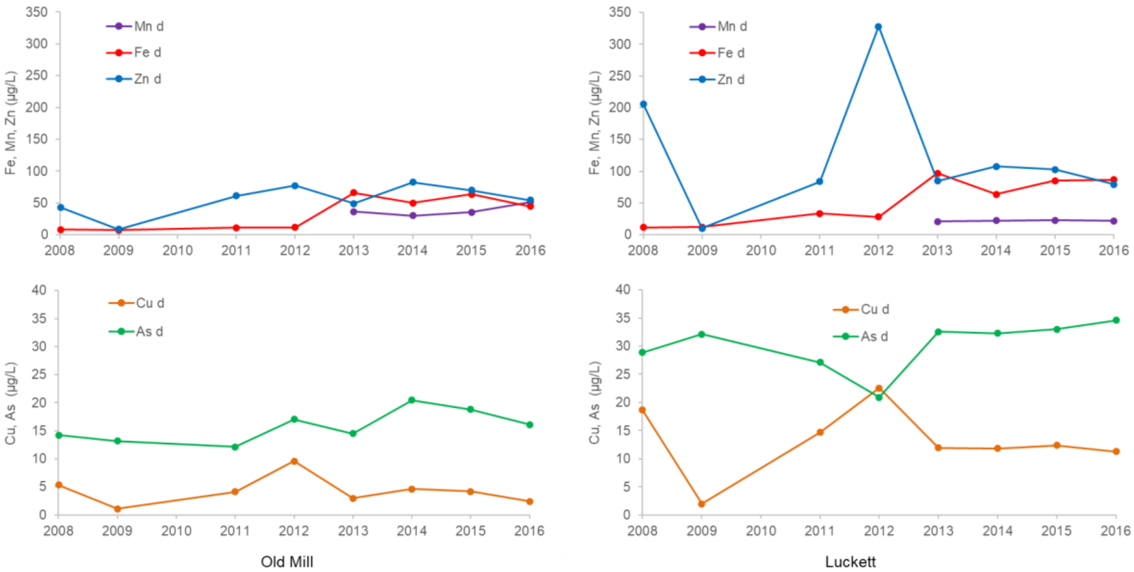

Figure 3-9 Dissolved metal/loid concentrations determined in water samples taken each October between 2008 and 2016 in Luckett Stream at Old Mill (left) and Luckett car park (right). Unpublished data, C Braungardt.

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3.6 Sediment Quality

During the October surveys (2008 to 2016) and as a one-off survey by Miganetara [12], sediment samples were taken in Luckett Stream at OM W and NGC W, as well as in Deerpark Stream (DP W, Figure 2-5). Both sets of data (Table 3-3) show iron concentrations in the Luckett catchment were within the typical range for the Tamar catchment, not exceeding the 'background' values established by [12] for the upper Tamar. In contrast, concentrations of Cu, Zn and As were clearly elevated by comparison to the upper Tamar catchment, and within the ranges for these metals established as typical by [12] for adits and streams in the Gunnislake/Calstock/Tavistock mining area. Concentrations determined in samples from the October surveys were consistently higher than in the NGC W sample taken by [12], and data in Table 3-3 illustrates more generally the variability of sediment metal/loid concentrations.

Table 3-3 Metal/loid concentrations in sediment samples taken each October between 2008 and 2016 in Luckett Stream at Old Mill and Luckett car park, as well as in Deerpark Stream (labelled 'October Surveys', unpublished data, C Braungardt). The data labelled 'Tamar Catchment' is a sub-set of samples taken for a larger project by [12]. Stdev: standard deviation for the average of eight surveys, Upper Tamar: sediment samples from the Tamar, Deer, Carey and Ottery, Mining Area: samples from 25 streams and adits in the Gunnislake/Calstock/Tavistock mining area, Luckett: sample taken in Luckett Stream at the car park downstream of NGC mine (raw data provided by K Mighanetara).

	October Surveys 2008-2016						Tamar Catchment		
	Old Mill		Deerpark		Luckett		Upper	Mining	Luckett
Parameter	Mean	Stdev	Mean	Stdev	Mean	Stdev	Tamar	Area	Stream
Fe (g/kg)	55	19	58	1	49	2	40-76	32-350	27
Cu (mg/kg)	540	190	330	11	770	73	40-80	400-28000	244
Zn (mg/kg)	1100	380	1000	34	1300	140	100-200	70-2700	355
As (mg/kg)	1400	480	980	39	2175	198	20-80	800-25000	680
Pb (mg/kg)	240	81	200	7.7	210	8.7			

During October Surveys (2008-2016), the stream bed was characterised and all necessary data collected to calculate the expected biological indices and determine measured indices from identified fauna collected by kick-sampling using the River Invertebrate Prediction & Classification Systems (RIVPACS) and River Invertebrate Classification Tool (RICT [33]). The results show slight variations between the three locations in the Luckett catchment (OM, NGC and DP) for each, BMWP (Biological Monitoring Working Party [34]), ASPT (Average Score Per Taxon) and NTAXA (taxonomic richness). The BMWP score is based on the presence or absence of macroinvertebrate (MI) families and is sensitive to organic pollution (sewage, farm run-off, biochemical oxygen demand). Scores at all three sites were well below the expected (Table 3-4), indicating that the community structure may be skewed towards species with higher tolerance to pollution. The ASTP is based on the fact that different MI families have different tolerance to contaminants and is calculated the average of all the tolerance scores, on a scale of 0 to 10, of the MI families detected. ASTP is independent on family richness and showed a different picture to BMWP: expected and measured were similar. However, the taxonomic richness (NTAXA) was again lower than expected at all sites, indicating reduced biodiversity.

Table 3-4 Expected and determined biological indices for the locations OM W and NGC W in Luckett Stream and DP W in Deerpark Stream from data collected during the October Surveys. Unpublished data, C Braungardt. BMWP: Biological Monitoring Working Party, ASPT: average score per taxon, NTAXA: taxonomic richness. Unpublished data kindly provided by R Goddard.

	Old Mill		Deerpark		Luckett	
Index	Expected	Measured	Expected	Measured	Expected	Measured
BMWP	129	75.3	110	74.3	128	66
ASPT	6.0	6.0	6.2	6.8	5.7	5.3
NTAXA	18.2	12.8	15.2	10.8	20.7	13.0

3.7 Preliminary Evaluation

3.7.1 Sources: Mining Waste and Buildings

Compared with the concentrations of metal/loids in UK [3] and wider Tamar Catchment soils [2], archive data at NGC Luckett shows extremely high enrichment factors for the median concentrations of arsenic (EF=1620 and 502, respectively), while tin, copper and lead featured moderate EFs. (Table 3-5).

Table 3-5 Range, average and median concentrations of metal/loids in rural soils in the UK [3] and the Tamar Catchment [2], compared with the range and median of available archive data at New Great Consols Mine, Luckett. EF is the calculated enrichment factor at NGC with respect to the medians.

Element	United Kingdom (n=366)			Tamar Catchment (n=468)			NGC (n=12)			EF UK	EF Tamar
(mg/kg)	min	max	median	min	max	median	min	max	median	median	median
As	0.50	143	7.1	6.8	15000	22.9	590	24000	11500	1620	502
Cu	2.3	97	17	2	2655	30	76	850	145	8.4	4.9
Mn	10	12200	420	77	33300	1550	91	1600	146	0.3	0.1
Pb	2.6	7.1	37	14	532	36	73	1000	295	7.9	8.3
Sn	2.0	115	2	2	610	5	100	190	120	60	23
Zn	2.6	442	66	128	575	229	16	490	31	0.5	0.1

The British Geological Survey G-Base data for the Southwest [35] highlights the area of Tavistock/Calstock/Gunnislake as hotspot for a range of metal/loids in soils, listed here as the concentration of the maximum percentile within this district, with the 50%ile in brackets:

- 8.55% by weight Fe (95%ile), (5.65%)
- 2792 mg/kg Mn (95%ile), (985 mg/kg)
- 1949 mg/kg As (100%ile), (23 mg/kg)
- 2831 mg/kg Cu (100%ile), (27 mg/kg)
- 385 mg/kg Sn (99%ile), (7.8 mg/kg)
- 383 mg/kg Zn (99%ile), (78 mg/kg)
- 280 mg/kg W (100%ile), (3.1 mg/kg)
- 532 mg/kg Pb (100%ile), (40 mg/kg)

This data places contamination at NGC (Table 3-1, Table 3-5) into a regional perspective: for most elements (except Fe and Mn), concentrations in mine spoil samples are elevated with respect to the 50%ile. However, regarding this highly mineralised area, concentrations could be regarded as 'typical' for Fe, Mn, Cu, Pb, Sn and Zn, but highly elevated for arsenic.

High arsenic contamination can be confirmed when comparing the data to typical concentrations in argillaceous sediments (13 mg/kg, [36]) and average concentrations in Cornish soils (90 mg/kg As [37]). This contamination is largely related to the deposition of contaminated gaseous emissions associated with the calciner furnace, labyrinth and chimneys, as well as material spills during transport along tramways. More severe contamination, such as determined at the New Great Consols mine site (up to 24000 mg/kg As), is typically present in mining waste material and close proximity to chimneys and ore dressing sites. The physico-chemical characterisation and evaluation of contaminant mobility and mineralogy suggests that the materials collected at NGC1 and NGC2 were generated from different ore material and subjected to different processes. For example, Cu is elevated at NGC2/Site 3, but much lower in NGC1/Site 2. Considering the materials as sources of contamination, the bare spoil heap (NGC1/Site 2) is exposed to weathering, wind, the impact of precipitation, infiltration and leaching, surface erosion and footfall. The relatively high mobility of arsenic and iron makes this heap a source of dissolved contaminants, whether leached in situ and exported in the dissolved phase, or transported via particles and then dissolved in rivers, the soil solution, or after ingestion or inhalation. The latter should be considered in risk assessments for any works carried out on site (see Appendix in Section 9).

In contrast, contaminants are less likely to be mobilised *in situ* from the tailings (NGC2/Site 3) in the valley floor and their main contamination pathway is likely to be erosion into the stream and via footfall and other recreational use. High particle loads in surface water flows from this area were observed during rainfall events in 2006 (Figure 3-4). The high extractability of lead is an exception, and considering the low pH, indicates that the tailings are a source of dissolved Pb to the river.

Samples from Sites 1, 4 and 5 have been characterised in less detail, but the wide-ranging concentrations of As, Fe, Mn, Pb and Zn and pH suggest equally diverse origins of these materials, as well as potential for metal/loid mobilisation, especially from material at Site 4, which features extremely low pH (1.8-2.1).

However, the very limited number of soil/spoil samples available for this report does provide a rough overview over the range of concentrations at the site. The site of NGC has experienced many changes over its history and as the study by Camm *et al* [37] on another Cornish site illustrates, a clear picture of contamination hot spots requires a detailed survey. Furthermore, to understand the potential for metal mobilisation from mine waste heaps via leaching, cores would have to be analysed.

The dissolution of efflorescent salts is an important mechanism for increasing the flux of dissolved metals from mine waste dumps and underground mine workings and has been identified as contributor to seasonal cycles in contaminant loading in water courses [38] [39] [40] [41]. Given their high mobility, efflorescent salt deposits in calciners and associated infrastructure at NGC may add to the loading of contaminants, in particular As, Cu and Sn, to Luckett stream via shallow groundwater and surface transport.

3.7.2 Pathways and Receptors: Sediment and Water

Whether via surface run-off, groundwater transport, adit flow or inputs of particles, the water bodies and their biota – in this case Luckett Stream – are receptors of mining related contamination, as well as being pathways to downstream locations and biomagnification.

Mine waste particles may enter the stream and become entrained as suspended load or deposited in the sediment. Within the stream system, sediments play an important role in regulating water quality, both serving as sinks and sources of contamination through (bio)geochemical cycling. Sediment biota, such as invertebrates and meiofauna, are important elements of aquatic ecosystems and, when in contact with contaminated sediments, may suffer (sub-)lethal effects that affect biodiversity, community structure and biomagnification of contaminants in the food web. The biological indices calculated for the Luckett catchment show a clearly impacted system with reduced macroinvertebrate biodiversity and a contamination tolerant community structure. Although BMWP has been designed with organic pollution in mind, the metal contamination of the sediment exceeds sediment quality guidelines at all three locations in the catchment for copper, zinc, arsenic and lead several-fold, most notably for arsenic (up to 369-fold) and copper (up to 22-fold, Table 3-6). The Canadian effects-based approach for Interim Sediment Quality Guidelines (ISQG) and Probable Effect Levels (PEL, [42]) were used here, because to date, the definition of EQS for freshwater sediments by the UK and EU is work in progress.

Table 3-6 Canadian Interim Sediment Quality Guidelines (ISQG) and Probable Effect Level (PEL) for Cu, Zn, As and Pb [42] and ratios of average measured concentrations in Luckett Stream at Old Mill (OM) and Luckett (NGC) and in Deerpark Stream (DP) to ISQG and PEL, respectively. Unpublished data, C Braungardt.

Parameter	ISQG	OM/ISQG	DP/ISQG	NGC/ISQG	PEL	OM/PEL	DP/PEL	NGC/PEL
Cu (mg/kg)	**36**	15.1	9.2	22	**197**	2.7	1.7	3.9
Zn (mg/kg)	**123**	8.9	8.1	11	**315**	3.5	3.2	4.1
As (mg/kg)	**5.9**	237	166	369	**17**	82	58	128
Pb (mg/kg)	**35**	6.9	5.7	6.0	**91.3**	2.6	2.2	2.3

The British Geological Survey G-Base data for the Southwest [2] identified the area of Tavistock/Calstock/Gunnislake as hotspot for a range of metal/loids in sediment, listed here as the concentration of the maximum percentile within this district, with the 50%ile in brackets:

- >358.65 mg/kg As (99%ile), (>15 mg/kg)
- >324.8 mg/kg Cu (99%ile), (>31.5 mg/kg)
- >248.45 mg/kg Sn (99%ile), (>3.1 mg/kg)
- >914.7 mg/kg Zn (99%ile), (>127.7 mg/kg)
- >151.55 mg/kg W (99%ile), (>3.1 mg/kg)
- >151.15 mg/kg Pb (99%ile), (>28.5 mg/kg)

Luckett stream sediments were at the higher end of the Tamar catchment concentration spectrum for As, Cu, Zn and Pb and clearly elevated above the 99%ile value for As, Cu and Zn. With the exception of arsenic, sediment concentrations were only slightly higher at Luckett compared to Old Mill (Table 3-3). Sediment concentrations of Fe, Zn and Cu were equal or higher (Table 3-3) than concentration ranges of these metals in the mine waste at NGC (Table 3-1). In contrast, As and Pb concentrations were higher in the mine waste material. Mineralogical analysis of the stream sediment samples highlighted the low abundance of scorodite at NGC (0.12%), even though the mine waste samples from the site contained 64% of the mineral by weight [30]. These differences between metals and the variability of metal/loid concentrations in the stream sediment samples over time indicate that hydrological and geochemical processes impact on the sediment composition:

- Erosion of soils from the mainly agricultural catchment provides a 'diluting' effect once soils settle as sediment in the streams.
- Fine-grained mine waste eroded at NGC and entering the stream may not settle on the stream bed or be readily resuspended during high flow conditions and transported into the Tamar.
- Geochemical cycling of metal/loids, including dissolution and precipitation effected by changing redox conditions and pH, as well as adsorption/desorption processes associated with iron and manganese (oxy)hydroxide phases – these processes differ for each mineral and metal/loid.
- The oxidation and dissolution of primary (sulfate) minerals in the eroded mine waste have the potential to release acid and metal/loids as 'acid mine drainage' (AMD) to the water, sediment and interstitial waters within the river, whether in the Luckett Stream of further downstream in the Tamar.

The results of monthly flux estimates (Figure 3-8) indicates that a significant proportion of the contamination in the winter months is transported in the particulate form, either from erosion of solids and input into the stream or from the suspension of bed sediment. In summer, fluxes were lower and the dissolved phase was generally the stronger source. It would be worth conducting a detailed site inspection to establish any point sources, such as adits in the catchment, although Mighanetara *et al* [32] established that overall, diffuse sources were the dominant contributors to metal flux in the Tamar.

Whether or not the dissolved concentrations of metal/loids in the stream were the result of adit discharge, run-off or erosion, comparisons with Environmental Quality Standards (EQS) for freshwater indicate potential exceedances for some metals in the Stream.

The freshwater EQS in the UK are based on annual averages:

- 50 µg/L As total concentration
- 123 µg/L Mn total concentration
- 1000 µg/L Fe dissolved concentration
- 1 µg/L Cu dissolved, bioavailable concentration
- 4 µg/L Ni dissolved, bioavailable concentration
- 10.9 µg/L Zn dissolved, bioavailable, plus ambient background concentration
- 1.2 µg/L Pb dissolved, bioavailable concentration

Although the dissolved arsenic concentration was above the EQS of 50 µg/L As in some of the water samples considered here, overall, the EQS based on annual averages for As, Mn and Fe was not exceeded for the data generated by [12].

Table 3-7 Application of the bio-met bioavailability tool [43] to calculate the bioavailable concentrations of specific and priority pollutants within the Water Framework Directive, using the Biotic Ligand Model (BLM) for water samples taken in the Luckett catchment. Columns highlighted in grey and blue refer to the October surveys, and orange is based on monthly surveys by [12]. DOC: dissolved organic carbon, Cu d: measured dissolved Cu concentration, Local Cu HC5: 5th percentile of a species sensitivity distribution, Cu bio: bioavailable Cu concentration, RCR: Risk Characterisation Ratio, RCR values in ***red*** *indicate risk, EQS-bio: the Water Framework Directive (WFD) Environmental Quality Standard (EQS) for the bioavailable dissolved metal fraction.*

	Old Mill		Luckett		Luckett	WFD
	October Average	Oct-15	October Average	Oct-15	Annual Average	EQS-bio (µg/L)
pH	6.98	5.51	6.74	5.48	7.02	
DOC (mg/L)	4.0	3.6	2.6	2.4	3.5	
Ca (mg/L)	16.2	17.2	13.1	13.7	19.0	
Cu d (µg/L)	4.3	4.2	13.0	12.4	45.0	1
Local Cu HC5 (µg/L)	15.5	3.1	9.0	2.1	14.5	
Cu bio (µg/L)	0.3	1.3	1.5	5.8	3.1	
Cu RCR	0.3	**1.3**	**1.5**	**5.8**	**3.1**	
Ni d (µg/L)	2.6	2.8	2.2	2.4	15.0	4
Local Ni HC5 (µg/L)	11.3	11.5	11.7	13.0	10.9	
Ni bio (µg/L)	0.9	1.0	0.8	0.7	5.5	
Ni RCR	0.2	0.2	0.2	0.2	**1.4**	
Zn d (µg/L)	55.8	70.1	125.0	103.0	80.0	10.9
Local Zn HC5 (µg/L)	20.4	16.9	15.1	15.7	18.9	
Zn bio (µg/L)	29.8	45.3	90.3	71.6	46.1	
Zn RCR	**2.7**	**4.2**	**8.3**	**6.6**	**4.2**	

To calculate the biologically available concentration of Cu, Ni and Zn specific to the Luckett Stream, the Bio-met Bioavailability Tool [44] of metals for the Water Framework Directive (WFD) was used. For this, the pH, dissolved metal, calcium and dissolved organic carbon (DOC) concentrations for samples were entered into the tool, which calculated the bioavailable metal concentrations, local HC5 and Risk Characterisation Ratio (RCR) (Table 3-7). HC5 is the 5th percentile of a species sensitivity distribution and therefore the concentration that protects 95% of the species and used to derive EQS. RCR is derived by dividing the local bioavailable metal concentration by the WFD EQS-bio (bioavailable) concentration and indicates a risk to biota when RCR ≥ 1. Although the WFD EQS-bio values are applied to annual averages, for illustrative purposes, they were also applied to the averages of the October data set (Table 3-7).

On the basis of the Bio-Met Bioavailability Tool calculations, the WFD EQS-bio were exceeded for Cu, Ni and Zn (but not for Pb, data not shown) in Luckett Stream downstream of NGC mine. Data from the October surveys indicate that the EQS for Cu and Zn may be exceeded at Old Mill at times. It should be noted that the latest version of the Bio-Met Bioavailability Tool does not add the ambient background concentration for Zn, following recent WFD guidance [44]. The joint report by the Environment Agency, European Copper Institute and International Lead Zinc Research Organisation (Table 5.4 in [45]) provides ambient background concentrations of Zn between 2.0 and 4.0 µg/L for the Southwest region and Tamar catchment. By applying the highest value, the local Zn EQS increases to 14.9 µg/L Zn-bio and this is still exceeded for all cases presented in (Table 3-7). Hence, failure of EQS for Cu, Ni and Zn can be confirmed for the year 2005/6 in Luckett Stream.

The water quality data at Old Mill suggest that metal/loid contamination sources exist in the headwaters of Luckett Stream. Some evidence of this has been provided by the work of William Stott in research associated with his undergraduate dissertation undertaken in collaboration with Cornwall Resources in 2017/18. Water samples taken in the southernmost branch of Luckett stream, just downstream of Holmbush mine contained averages of 230 µg/L Zn, 44 µg/L Cu, 36 µg/L As, 4.3 µg/L Ni and 0.74 µg/L Cd, with WFD EQS and EQS-bio, respectively, exceeded by an order of magnitude for Cd, Zn and Cu [46]. Although only a snapshot in time, these results clearly indicate that failure of environmental quality standards in Luckett Stream cannot be solely attributed to contamination arising at New Great Consols mine.

4 Environmental Status of New Great Consols

4.1 Aims and Scope

The aim of this section is to provide a picture of the environmental status of the New Great Consols mine site today (2023). This will be achieved through walkover surveys, comparisons of contemporary with archive data and photographs that were presented in Section 3 of this report. Two new, detailed analyses of environmental conditions are included for the purpose of elucidating sources and pathways of contamination: (i) a high resolution surface soil survey and (ii) a catchment survey of water quality.

4.2 Non-technical Summary

New investigations and analyses of available data provided no evidence that the water quality in Luckett Stream has improved or deteriorated over the time period considered in this report (2005 to 2023). The catchment can be considered in three zones, each characterised by different influences on water quality, which are captured in a diagram in the discussion (Section 4.7):

1) Upper catchment upstream of Old Mill:
    - weathering of bedrock and soil,
    - agricultural activities and run-off,
    - water industry outlet and septic tanks,
    - particles and acidic mine waters rich in metals and arsenic from Holmbush and Downgate mines.
2) Lower catchment between Old Mill and Luckett:
    - agricultural activities and run-off,
    - septic tank effluent,
    - woodland, potentially providing attenuation of agricultural run-off,
    - particles and acidic mine waters rich in metals and arsenic from Great Sheba Consols, Kelly Hole and Wheal Martha mines,
    - Deerpark Stream, providing some dilution.
3) New Great Consols mine site at Luckett:
    - complex and diverse sources of particles and acidic mine waters rich in metals and arsenic,
    - some evidence of attenuation and/or dilution within the site.

The detailed analysis of surface soils confirmed the highly polluted status of NGC and allowed the spatial analysis of contamination sources to the stream. Given the toxicity of the mine wastes, their low nutrient concentrations, acidity and lack of humus, the vegetation cover established naturally on NGC is surprisingly extensive. Habitat types range from woodland and shrub on higher ground to heath, bog and grassland covering much of the valley floor. The species present are known for their strategies to adapt to the challenging conditions prevailing on the site and more detailed species identification and associated soil characterisation could be of value for planning site remediation.

The parts of the site that remain barren include paths and other areas that are compacted by trampling, steep slopes of mine waste dumps, the steep sides of tailings at the riverbank and highly contaminated areas around the calciners. Bare mine waste is of particular concern because of its exposure to erosion and leaching. Vegetation affords protection from the physical processes that contribute to spreading of contamination, it reduces the

- wind velocity and hence the wind-blown erosion and dispersion of solids,
- rain-induced erosion, run-off and freeze-thaw erosion through providing cover,
- run-off and gully erosion by binding substrate with roots and providing cover,
- rain infiltration through evapotranspiration (spring and summer), hence reduces leaching of mine waste and the potential for slope failure,
- compaction and erosion by footfall by hindering access.

Sub-surface sources of contamination are often invisible but are important for stream water quality. These include acidic, metal and arsenic-rich leachates, called acid mine drainage (AMD), which is generated when water and oxygen are in contact with the ores that remain in the waste heaps left by the mining and ore processing activity. After heavy rainfall in January 2023, AMD on the NGC site surfaced as small springs and accumulated in puddles, where it was sampled before entering the stream. However, even in drier weather, AMD will be generated and transported invisibly with shallow groundwater until it enters the stream bed from below ground. Such inputs can only be quantified with boreholes, but the AMD collected during a period of heavy rain at the surface provides an indication of concentrations and confirmed its high pollution potential at NGC.

Overall, NGC presents a complex mixture of contaminated materials, including the walls of buildings, as well as mine wastes of different origin, composition and grain sizes. Environmental Quality Standards for zinc and copper dissolved in Luckett Stream were exceeded at Old Mill and Luckett car park, highlighting that contamination inputs to the upper catchment are an important consideration for assessing the contribution to the contamination of Luckett Stream by NGC.

4.3 Walkover Surveys 2022/23

Walkover surveys were carried out on 25/11/2022 and 12/01/2023 and relevant photographs are included here to provide a record of the visual site status and enable comparisons to images provided in Section 3.3.

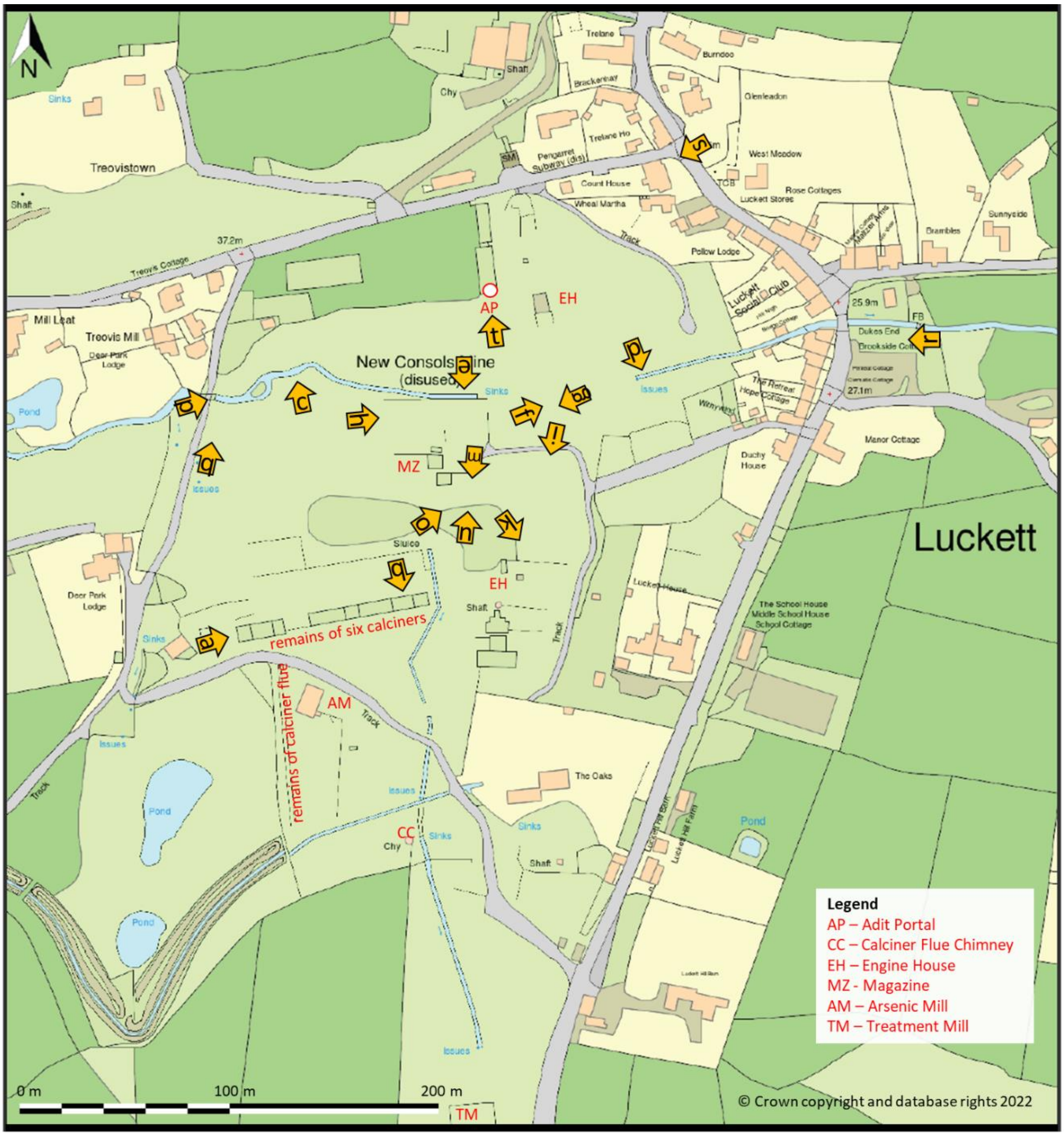

Figure 4-1 Map indicating angles where photographs were taken (yellow arrows), with lettering corresponding to photographs in this section. Features recorded on site are noted in red (see legend). Site Plan shows OSGridRef: SX38757351 (mapserve.co.uk, a licensed Ordnance Survey partner (100053143). Map base © Crown copyright and database rights 2023 Ordnance Survey 100049047.

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Much of NGC is vegetated with a mixture of broadleaf woodland dominating the high ground in the narrow southern part of the site, where remains of buildings and concrete structures from mine workings in the early 20th century are hidden among trees and undergrowth. The site widens between the calciner chimney (Figure 4-1) and the calciner row, the generally sloping ground undulates and it is covered in scrubby broadleaf woodland, with hazel and a proliferation of brambles and ivy. From the calciner row into the valley bottom, the site is partially vegetated and characterised by a range of grey/beige sandy spoil heaps with largely barren steep slopes, whitish and red-brown tailings and remains of buildings among low scrub and birch trees. The vegetation resembles elements of lowland heath with gorse, bramble and heather. Grasses and lower plants (mosses, bryophytes) form the interface of vegetation and bare areas of ground and paths. Between the stream and the road that connects Luckett with Treovis Mill, the ground rises and woodland trees, bramble, shrubs and bare ground form a mosaic among which features, such as the crushing engine, adit, shafts and culvert portals are obscured. In this area, wetland conditions prevail at least seasonally. Overall, the vegetation today resembles the classification of deciduous woodland, bog, grassland and dwarf shrub heath marked in the Priority Habitat Inventory by the UK Government (Section 2.6).

Figure 4-2 Images taken at the row of calciners at NGC, showing individual calciners in various states of repair. The top right image offers a view over the top of the calciner row. Compare with Figure 3-5 from 2005 in Section 3.3. Yellow arrows correspond with viewing angles in Figure 4-1. Photos: C Braungardt 2022.

A row of six calciners is located within the boundary of NGC (Figure 4-1) on elevated ground, approximately 30 metres above Luckett Stream and 10 metres above the mine spoil heap marked on the map. The structures are generally in poor repair, with barrel vaults having partially collapsed, although walls are mainly intact (Figure 4-2). Calcination has been applied to obtain arsenic trioxide from arsenopyrite as raw material for insecticide and pigment manufacture, and to purify tin ores contaminated with sulfur and arsenic. It is likely that the substrate surrounding the calciner structures are highly contaminated, and this merits further investigation. Vegetation surrounding the calciners is sparce, and the species present are likely to be resilient to contaminated conditions, which is of value when selecting locally adapted plants for remediation purposes.

Figure 4-3 Images taken at the row of calciners at NGC in November 2022, showing the inside of two calciners with collapsed roofs, each in a separate row. Detailed photos of the interior show thick, whitish blooms of efflorescent salts and turquoise and ochre metal precipitates on the brickwork. Deposits at the floor of the calciners originate from collapsed roofs and include bricks and mortar impregnated with arsenic, sulfur and metal fumes during calcination and potentially efflorescent salts fallen from the brickwork. Compare with Figure 3-5 from 2005 in Section 3.3. Photos: C Braungardt 2022.

To extract arsenic from sulfide ores, the calcination process involved heating the ore to a temperature at which arsenic oxidises and sublimes, i.e. turns from the solid into a gas without liquification. Subsequently, the arsenic fumes were condensed in a folded brick chamber, or labyrinth, where arsenic trioxide precipitated on surfaces to be scraped out and sold. As a result, porous surfaces, such as bricks and mortar within the calciner, labyrinth, flue and chimney became impregnated with a toxic mixture of gases containing a high proportion of arsenic.

The interior of calciner structures featured efflorescent salts in 2005 (Figure 3-5) and are still ‘blooming’ thick layers of whitish (arsenic-rich) crystals and turquoise (copper-rich) precipitates today (Figure 4-3). These precipitates are toxic, soluble and a potential source of contamination for the surrounding soils, shallow groundwater and surface run-off. Similar efflorescent salts have been observed at the calciner chimney in the south of the site (Figure 4-1) and are likely to be present in the remains of the calciner flue leading from the calciners to that chimney. The area between the calciner row and chimney was not readily accessible among thick vegetation of bramble and shrubs and the structure and route of the flue could not be identified during the walkover survey.

The spoil heaps deposited on the slope between the row of calciners and the valley floor are mainly poorly sorted sandy material of a light grey to beige appearance (Figure 4-4, Figure 4-5). Flat surfaces at the top of these spoil heaps are partially vegetated with a mixture of heathers, gorse and grasses, with some ivy, mosses, lichens and bryophytes acting as ground cover. Below the slope break, erosion appears to continuously expose fresh surfaces, so that vegetation cannot establish. Erosion fans of lose material at the base of the grey/beige spoil heaps were observed in 2005/6 (Figure 3-2) and are still evident today (Figure 4-5).

Ephemeral springs (Figure 4-5) emanate at the base of spoil heaps after heavy rainfall and through the erosion fans, forming small gullies. These small springs also carried particles and two were sampled as ES2 and ES4 in the contemporary catchment survey (January 2023). The results are discussed in Section 4.6.

Across the centre of the site, vegetation-free areas and paths of more compacted materials exist on both, sandy spoil and silty tailings. These are often the result of footfall and there is some evidence of recreational use, including bicycle tyre tracks and dog footprints. The erosion on north-facing mine spoil slopes is likely a combined effect of gravitational loss of material on steeper slopes, the impact of precipitation, wind erosion, freeze-thaw erosion and footfall by people and animals (e.g. grazing deer, rabbit burrows).

Figure 4-4 Illustration of physical processes that slow down natural revegetation of spoil heaps and tailings: surface erosion of steep slopes and compaction on paths due to recreational use (footfall, biking, bottom right). Compare also with images shown in Figure 3-2. Top row: yellow outlines show areas where cut vegetation has been placed on the slope. Yellow arrows correspond with viewing angles in Figure 4-1. Photos: C Braungardt 2022/3.

Vegetation requires a stable substrate for physical anchoring, nutrients and water, and the slopes of mine waste dumps are lacking in these features and are also contaminated with metal/loids and high acidity. As a result, the upper slopes of spoil heaps remain unvegetated (Figure 4-4). On the shallower lower slopes, where organic matter accumulates and water is more readily available, vegetation establishes over time. However, in some places, eroded material from upper slopes smothers the beginning of natural succession at the base of spoil heaps.

An attempt to reduce the slope erosion appears to have been made by placing cuttings of vegetation onto the slope (Figure 4-4). Spiny gorse clippings interlock, limit wind and water erosion, prevent footfall and through composting over time, will provide organic matter that encourages natural succession to take place.

Figure 4-5 Locations of samples (2) and (4) (Figure 4-23) from ephemeral springs near the base of spoil heaps January 2023. Sample (4) corresponds to the spoil heap at which the archive sample NGC1 was taken (Section 3) and the viewing angle [i] on the right image here corresponds to the reverse of viewing angle [a] in Figure 3-2. Contemporary images illustrate the increase in vegetation cover since 2005. Yellow arrows correspond with viewing angles in Figure 4-1. Photos: C Braungardt 2023.

Mine waste in the valley floor is fine-grained, silty material, originally deposited in lagoons as a slurry that, over time, de-watered and compacted, forming thick, level layers of tailings with low permeability and porosity. The establishment of vegetation on tailings is hampered by their tendency to become waterlogged, especially when compacted further by footfall. In addition, tailings typically contain low concentrations of nutrients and organic matter, are of low pH and contain high concentrations of potentially toxic elements (see Section 3.4). At NGC, deciduous woodlands established on parts of the site and the surrounding land provide leaflitter, which over time rots into a supply of organic matter, releasing nutrients and providing habitat for lichens, fungi and invertebrates. As a result, lowland heath and scrubby woodland has established on part of the tailings (Figure 4-5, flat areas beyond sampling point (4) and in front of sampling point (2)).

Another ready supply of organic matter is provided by clusters of rabbit faeces on bare ground (Figure 4-6), upon which fungi, bryophytes and mosses establish themselves. This process starts off natural succession that leads to the establishment of grasses, herbs, shrubs and trees over time. Consequently, lowland heath communities and scrubby woodland that were evident in two decades ago are more advanced and widespread today.

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Figure 4-6 Illustration of natural revegetation process at NGC induced by rabbits. Top left: cluster of rabbit faeces on bare mine tailings; top right: decaying faeces provide nutrients for fungi, lichen and mosses; bottom left: more organic matter accumulates (e.g. leaves, dying vegetation) and facilitates moisture and nutrient retention. Bottom right: natural succession brings bryophytes, grasses and eventually herbs, shrubs and trees to the site. Photos: C Braungardt 2022.

Waterlogging and saturation of soils and mine wastes was evident on 12th January 2023, with pools and streams of water on tailings across the valley floor (Figure 4-7). Water was supplied directly by heavy rain and from the ephemeral springs emanating from coarse spoil heaps between the calciners and valley floor to the south of the stream (Figure 4-5). Water samples (2, 4 and 5) taken from the surface water on site are discussed in Section 4.6.

Figure 4-7 Flooded NGC tailings in the valley floor after heavy rainfalls in January 2023. Running water from higher ground accumulated on tracks and bare ground in shallow ephemeral streams and lakes. Top middle: the front of my boots submersed in ephemeral stream (f) to illustrate depth. The image of viewing angle [h] from November 2022 (bottom left) has been included for comparison with the same view in January 2023. Water sample (5) was taken in January 2023 (Figure 4-23). Yellow arrows correspond with viewing angles in Figure 4-1. Photos: C Braungardt 2022/3.

Comparison of contemporary photographs (Figure 4-8) with those taken in 2005/6 (Figure 3-3) at sampling site NGC2 / Site 3 (Figure 3-1) indicate some erosion of the thick layer of white tailings that form the bank of Luckett Stream between the western boundary of the site and the culvert exit. In particular, an overhang present in the right hand image of Figure 3-3 is absent in the top right image of Figure 4-8, taken from the same angle.

Tailings are a direct source of fine grained, contaminated particles to the stream, where they may be incorporated into the sediment, transported further downstream and/or oxidise and dissolve over time, releasing metal/loids, acid and sulfate to the water column, with the potential to increase conductivity substantially.

Figure 4-8 Photographs taken at archive water sampling site NGC2 (see Section 3) in November 2022 (top row) and January 2023 (middle and bottom rows). Comparison with Figure 3-3 indicates some erosion of mine spoil from the banks of Luckett Stream since 2005/6. Detailed photographs (bottom row) show freshly exposed layering of mine waste deposits above the water line. Yellow arrows correspond with viewing angles in Figure 4-1 and water sampling site (6) in January 2023 (Figure 4-23). Photos: C Braungardt 2022/3.

Close-up images at the water line show a reddish-brown layer beneath the light-coloured fine grained mine tailings (bottom row and central image in Figure 4-8). The deposition of diverse materials at different phases of mining and ore processing at NGC occurred historically in the valley, presumably leaving the stream to find its way through the growing tailings until part of it was culverted to enable additional slurry lagoons to be established. The different layers of contaminated material remain as sources of contamination in close proximity of the stream and have not been investigated in detail.

Figure 4-9 Images of reddish-brown tailings at NGC, where they overlay the whitish tailings near the river bank, (top left and bottom right), or form the entire bank of the stream, for example at the culvert exit (top right image). The bottom left image shows pixie-cup lichens growing on rain-pitted tailings among organic debris. Yellow arrows correspond with viewing angles in Figure 4-1. Photos: C Braungardt 2023.

Reddish-brown tailing deposits are also evident as sole layer to the east of the culvert exit and as outcrops or superimposed onto white tailings in the valley floor elsewhere, in particular to the north of the stream (Figure 4-9). Analysis of surface soil samples taken in this area confirm elevated concentrations of Sn and As, as well as tungsten and silver (Section 4.4), which is of concern as this material appears to be prone to rain-pitting and erosion (Figure 4-9).

Figure 4-10 The stream ahead of the entrance (top row) and beyond the exit (bottom row) of the culvert within the site, under high flow conditions on 12 January 2023. Compare with Figure 3-4. Yellow arrows correspond with viewing angles in Figure 4-1 and water sampling sites (1) and (3) in January 2023 (Figure 4-23). Photos: C Braungardt 2023.

In January 2023, water sampling was carried out after a prolonged period of heavy rainfalls. Luckett Stream was in a state of high, turbid and turbulent flow, illustrated in images of the culvert entrance and exit in Figure 4-10. Water flow rates were not determined during contemporary surveys, but measured during monthly surveys in 2005/6 (archive data, Section 3) and showed that both, water flow and contamination fluxes were at their highest levels between November and February (Figure 3-8), when particulate matter concentration were also at their highest.

At the western extreme of the NGC site, the origin of a small side stream is marked as ‘issues’ on the Ordnance Survey map (Figure 4-1), although the stream itself is not shown, possibly because it may be ephemeral. It was flowing in November 2022 and January 2023, when it was sampled (7) and photographed (Figure 4-11).

Figure 4-11 Locations of samples (7) in a side stream to Luckett Stream, (8) upstream of their confluence, and (9) at Luckett car park downstream of NGC, taken in January 2023. Yellow arrows correspond with viewing angles in Figure 4-1. Photos: C Braungardt 2023.

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An adit portal near the crushing engine house (location t, map Figure 4-1 and Figure 4-12) permitted a view inside a well-preserved tunnel leading north beneath a linear structure on the surface. The adit portal is fenced and the ground in front of it has been made up. The water was clear and moving slowly in a southerly direction below the surface of the made ground, and it is unclear whether the water soaks away or is contained in a culvert leading to the stream. No sample could be taken with the equipment available.

As a point of interest, a wall featuring efflorescent salts similar to those found at the calciners and calciner chimney, was noted facing the road at an intersection in the village (Figure 4-12). This should be investigated for the presence of potentially toxic elements that could create an additional source of contamination to Luckett Stream with road surface run-off.

Figure 4-12 Structures associated with the mine site include the Count House (yellow arrow [s] in Figure 4-1), that features a road-facing section of wall upon which efflorescent salts and metal precipitates are evident (left block of photographs). The adit portal is marked [t] in Figure 4-1 and is the entrance to a well-preserved tunnel that runs north, with water flowing south. Photos: C Braungardt 2023.

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The diversity of the mine waste on the NGC site is clearly visible, with dumps composed of materials originating from different processes carried out over time with progressively advanced technology: (i) the initial, coarse, crushing of rocks to remove most of the gangue (aggregate-sized) and (ii) further crushing and grinding into finer size fractions for the separation of mineral grains from gangue (sand- to silt-sized, depending on technology), which (iii) was achieved by the washing of ground material, which separated the ore from the gangue on the basis of gravity on buddles or later, shaking tables.

In summary, at NGC grey and beige sandy mine deposits are generally found in heaps with steep slopes facing downhill (e.g. Figure 4-5 & Figure 4-4), while the tailings in the valley bottom are finer-grained and deposited in layers of either a whitish (e.g. Figure 4-8 & Figure 4-6) or reddish-brown (e.g. Figure 4-9) sandy silt.

The potential for these deposits as contamination sources is largely based on the greatly increased surface area of processed metal ores still present in waste and its exposure to physical, chemical and biological weathering processes in the presence of oxygen and water (see glossary for more detailed account of acid mine drainage generation). The walkover surveys revealed a range of potential sources and pathways of contamination to Luckett Stream:

- calciner complex, flue, chimney: contaminated structures and surrounding soils, soluble efflorescent salts, contaminated dusts and rubble,
- calcination waste downhill and north of calciner row: potentially toxic elements, low pH, coarse material of high permeability and low cohesion, readily eroded and prone to surface run-off, readily permeated by water with potential for leachate export from base of spoil heaps carrying elements to the stream,
- fine grained tailings in valley bottom: direct erosion by the stream flow at the banks, erosion by surface run-off in high flow condition, wind erosion of dusts in dry periods, erosion by recreational activities and animals, limited permeability with some capacity for leaching of potentially toxic elements,
- mixed deposits of mine waste: different mineralogy and permeability in layers at depth may provide preferential flow channels for shallow groundwater and direct inputs of leachate into the hyporheic zone of the stream,
- unknown: sub-surface adits and/or drainage pipes into stream or culvert,
- animal activity, footfall and recreation: physical erosion, prevention of slope consolidation, compaction, hampering of natural revegetation, spreading of contaminated material further afield and off site.

Knowledge about the actual concentrations of potentially toxic elements across the site is limited to a few samples of sandy mine waste and tailings taken in the past across the centre of the site (see Section 3.4). In order to establish the extent of surface mine waste dumps and tailings at the site and their contamination, a detailed investigation of the potentially toxic element content of surface soils and spoil was undertaken in summer 2023.

4.4 Detailed Analysis of Surface Soil and Spoil

Permission to take surface samples at high resolution was granted by both, the landowners of NGC and Historic England. A total of 94 samples of surface soil, mine waste dumps and mine tailings were obtained across the whole NGC site on 18 and 19 May and 1 June 2023 (Figure 4-13). Samples were collected by researchers from Challenging Habitat (Dr Charlotte Braungardt) and the University of Plymouth (Dr Alison Turner, Dr Matt Baily Ross, Mr Mayowa Oyedara, Mr Emmanuel Ikhizama). At each location, the top layer of soil/spoil or, if present, the vegetation cover, was carefully removed with a trowel from five points within a square metre. Soil or mine waste samples were taken at 2-5 cm depth at each of these points with a PTFE spatula and combined into a composite sample in a Kraft bag. Any surface material disturbed by the sample procedure was restored as close to the original condition, as requested by Historic England. Samples were dried at the laboratories of the University and metal/loid concentrations determined by E. Ikhizama using XRF[1].

[1] It should be noted that XRF analysis has limitations with respect to the sensitivity of the method and is suitable for screening purposes only. Comparisons with analytical results for certified reference materials indicated an uncertainty in the accuracy of obtained values between 10 and 20%. More detailed chemical analyses and determination of element mobility forms part of research by E. Ikhiama towards an MSc thesis that is available from academic partners at the University of Plymouth in autumn 2023.

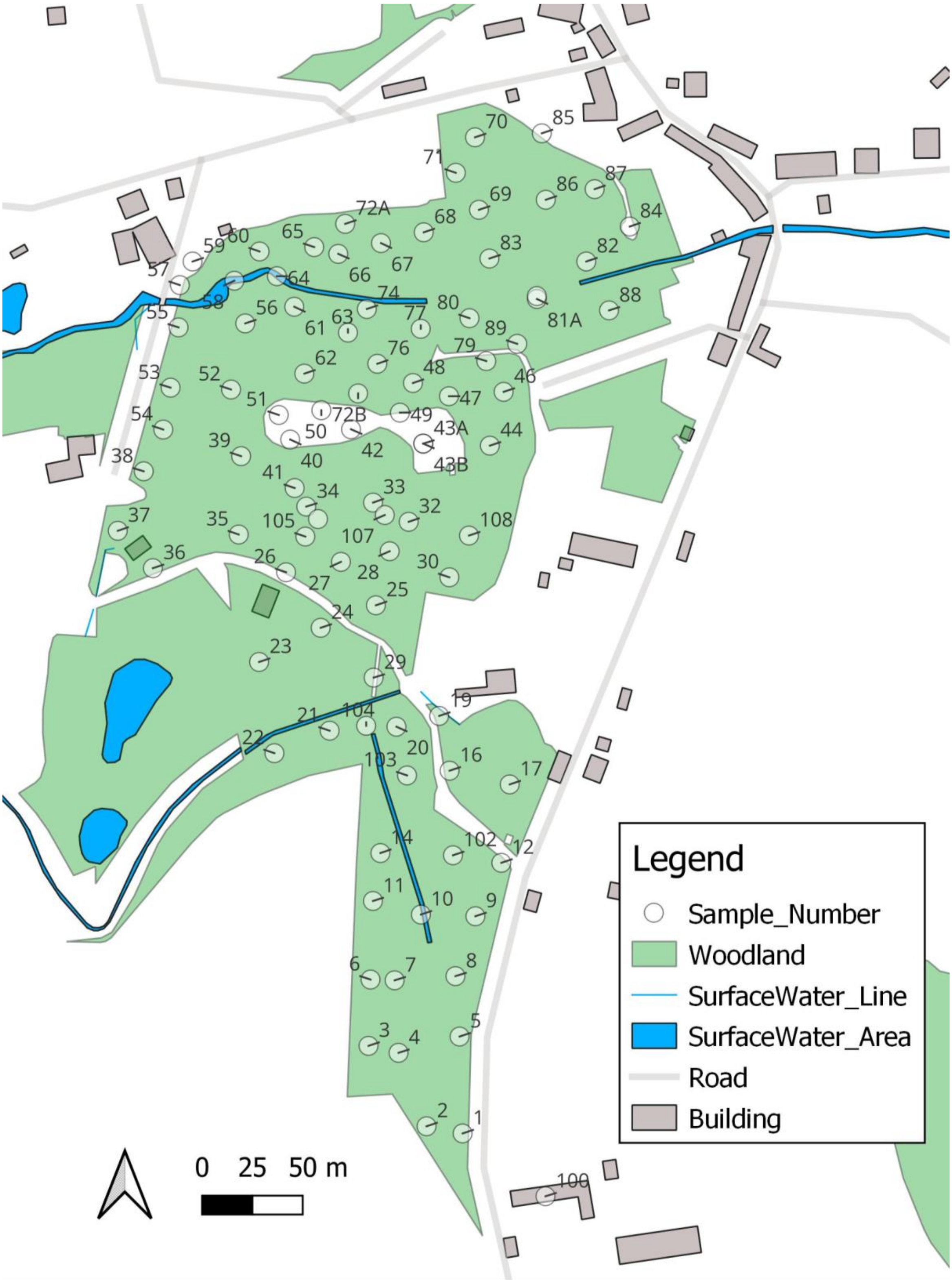

Figure 4-13 Sample points and numbers of surface soils at New Great Consols, May/June 2023. In the text, sample numbers are prefixed with 'S' to distinguish them from locations mentioned elsewhere in the report. Map base: OS OpenMap – Local, [Open Government License](#) © Crown copyright and database rights 2023 Ordnance Survey 100049047.

This detailed survey confirmed the highly polluted status of the site (Table 4-1) already suggested by evaluating limited archive data and in the British Geological Survey reports considered in Sections 3.4 and 3.7. While the new survey revealed lower minimum concentrations in areas of the site that had not been covered before, it also exposed pollution maxima that were an order of magnitude higher than previously known, especially in sample S7 in the southern part of the site (Figure 4-13), which otherwise features relatively low metal/loid concentrations and woodland vegetation (Figure 4-14). The survey included a wider range of metals, showing that Cr and V are relatively uniformly distributed on site.

Table 4-1 Summary statistics for metal/loid concentrations in surface soils at NGC and at the control sample obtained from a field to the southeast of NGC (CF) in May and June 2023. STDEV – standard deviation, RSD – relative standard deviation. LOD – limit of detection. Raw data courtesy of E. Ikhizama, University of Plymouth.

mg/kg	Zn	Cu	Sn	As	Fe	Mn	Pb	W	Sr	Cr	V	Ag
minimum	140	39	100	37	10000	88	48	76	21	57	26	5.0
mean	**510**	**680**	**2800**	**7600**	**84000**	**750**	**290**	**880**	**52**	**109**	**95**	**24**
median	**290**	**340**	**1800**	**2600**	**76000**	**780**	**250**	**520**	**48**	**109**	**93**	**14**
maximum	7600	10000	19000	170000	290000	1900	960	4100	127	208	158	110
STDEV	840	1300	3500	19000	37000	370	170	870	19	24	29	23
RSD (%)	170	190	130	250	44	50	61	99	37	22	30	96
Control (field)	380	260	190	360	51000	1045	180	<LOD	74	118	121	8.0

Figure 4-14 Photographs of a small, isolated tailings pile (sample S7) in the south of the NGC site that featured extremely high concentrations of Fe, As, Sn, Pb and W.

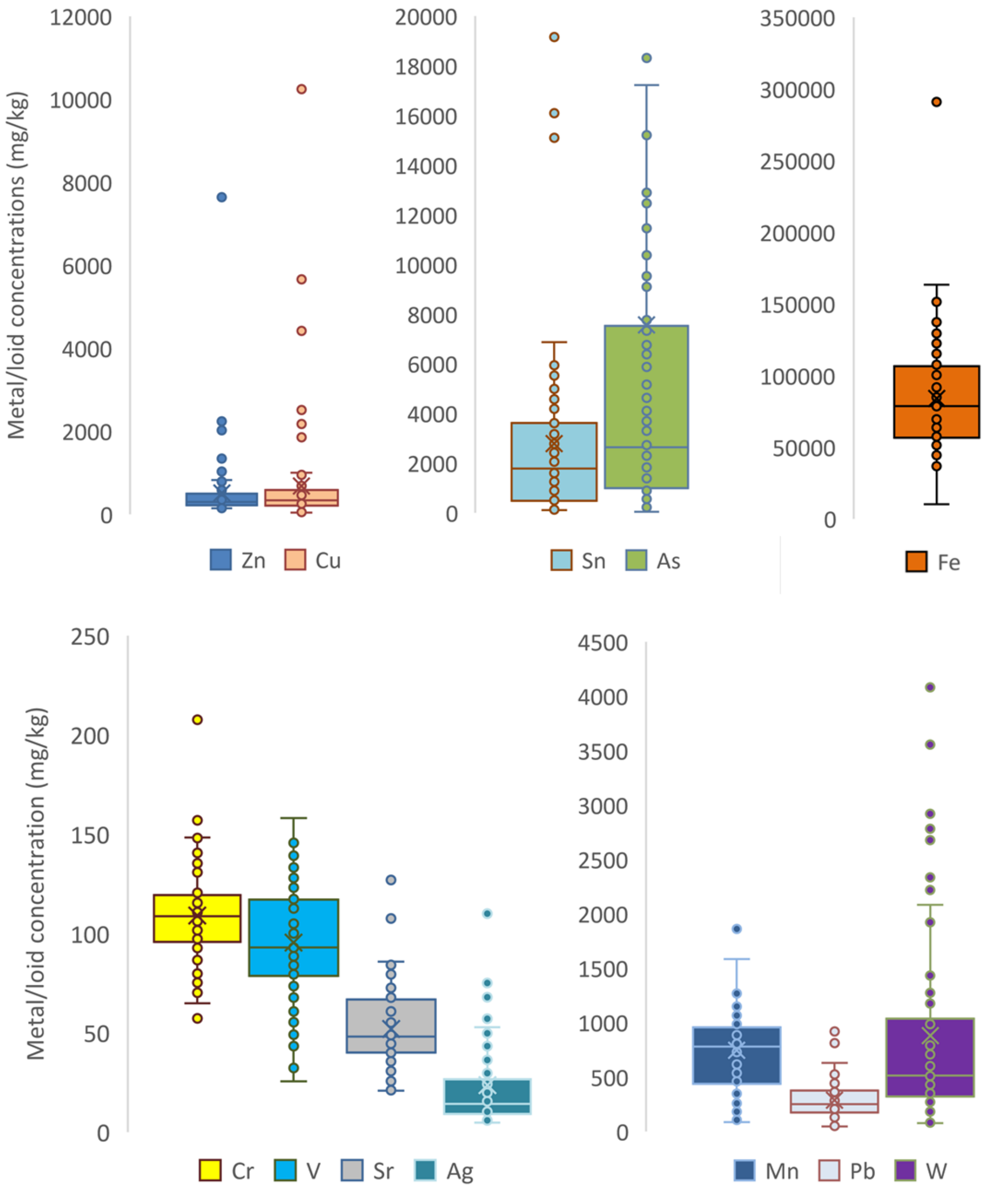

Figure 4-15 Box and whisker plot of metal/loid concentrations determined in 94 surface samples at NGC. The cross (x) and horizontal line in the box denote the arithmetic mean and median, respectively. Raw data courtesy of E. Ikhizama, University of Plymouth.

The concentrations of metal/loids in surface soils obtained in NGC exhibited high variability (Figure 4-15), with relative standard deviations (RSD) higher than 100% for Sn, Zn, Cu and As (Table 4-1). Large differences between arithmetic mean and median values indicate a high skewness in the data for Sn, As, W, Zn and Cu, and the presence of outliers that are one or two orders of magnitude above the mean and median show hotspots of concentration maxima that had not been identified by previous surveys. For example, the maximum concentrations of 19000 mg/kg Sn, 7600 mg/kg Zn 10000 mg/kg Cu, 170000 mg/kg As and 290000 mg/kg Fe obtained in this contemporary survey are higher by factors of 100, 16, 12, 7 and 4, respectively than maxima in archive data (Table 3-1, Section 3.4).

The results lead to a re-evaluation, compared to Section 3.7.1, of the contamination at NGC within the regional perspective: concentrations in some parts of the site are elevated with respect to the 95%tile (or higher) for Fe, As, Cu, Sn, Zn, W, Pb and Ag, but not for Cr, V or Sr. Even within this highly mineralised area, the hotspots of pollution (Figure 4-15) on site can be considered as 'extreme'.

The metal/loid concentrations (Table 4-1) at the control site in the field to the east of the southern extremity of NGC (Sample S100, Figure 4-13) were below the median on NGC for Cu, Sn, As, Pb, Fe, W and Ag, which were the dominant elements in ores processed on site. Zinc, Mn, Sr, Cr and V concentrations at the control site were either within the mean to median range or somewhat higher than at NGC, implying a closer alignment of these metals with the local background.

Examination of the spatial distribution of metal/loids (Figure 4-16 to Figure 4-19) prompted an exploration of the heterogeneity of the surface material by multi-variable analysis, which may hint at common mineralogy in mine wastes, geochemical transformations or deposition pathways in soils for correlated metal/loids.

The analysis returned strong positive correlations ($R \geq 0.8$) between Cu and Zn, as well as Ag and Sn. While Zn has not been mined in the Luckett catchment (Table 2-3), the metal occurs as the guest mineral sphalerite (ZnS) and also features as common impurity in iron minerals, such as pyrite and siderite (Table 2-2), which are abundant in the region. Waste materials generated as a result of arsenic, copper and iron ore processing at NGC mine are therefore likely to contain appreciable quantities of zinc, deposited in mine spoil and tailings along with copper that would be present either as guest mineral in As or Fe ores and/or incomplete extraction of Cu ores. Particularly high levels of both, Cu and Zn occurred in isolated spots throughout the site, including samples S26 and S34 on the rising ground between the row of calciners and the arsenic mill, in S104 at the calciner chimney and in S76 in white tailings near ruined ore processing buildings.

Moderately positive correlations (0.5≤R<0.7) between Fe, Sn, As, Pb and W are also likely to be related to the co-occurrence of ores in wastes, and may have been partially 'driven' by the concentration spikes of Fe, Sn, As, Pb and W in sample S7, as iron is otherwise relatively uniform in distribution (Figure 4-17). Tailings deposited north of the river exhibit a close overlap of As and Sn, elements that occur together in ore deposits of Wheal Martha. Both metals have been recorded as reworked from dumps at NGC in the early 20th century (Section 2.5). Similarly, the strong association of Ag and Sn in the mine waste (Figure 4-18, Figure 4-19) most probably relates to the outputs of NGC and Wheal Martha at the heyday of mining (Ag-bearing Cu precipitate and Sn ore), as well as reworking of dumps later on (Sn ore, Table 2-3).

Tungsten concentrations were below the limit of detection in most samples that did not contain mine waste upon visual inspection (Figure 4-19). Conversely, spoil and tailings samples featured W, with the highest concentrations in the areas surrounding the calciners, arsenic mill, calciner chimney, tailings north of the stream and south of the culvert, as well as samples from the main coarsely grained waste dumps and surrounding S7. Hence, areas with detectable W concentrations may be a rough indicator of mine waste being present in surface materials.

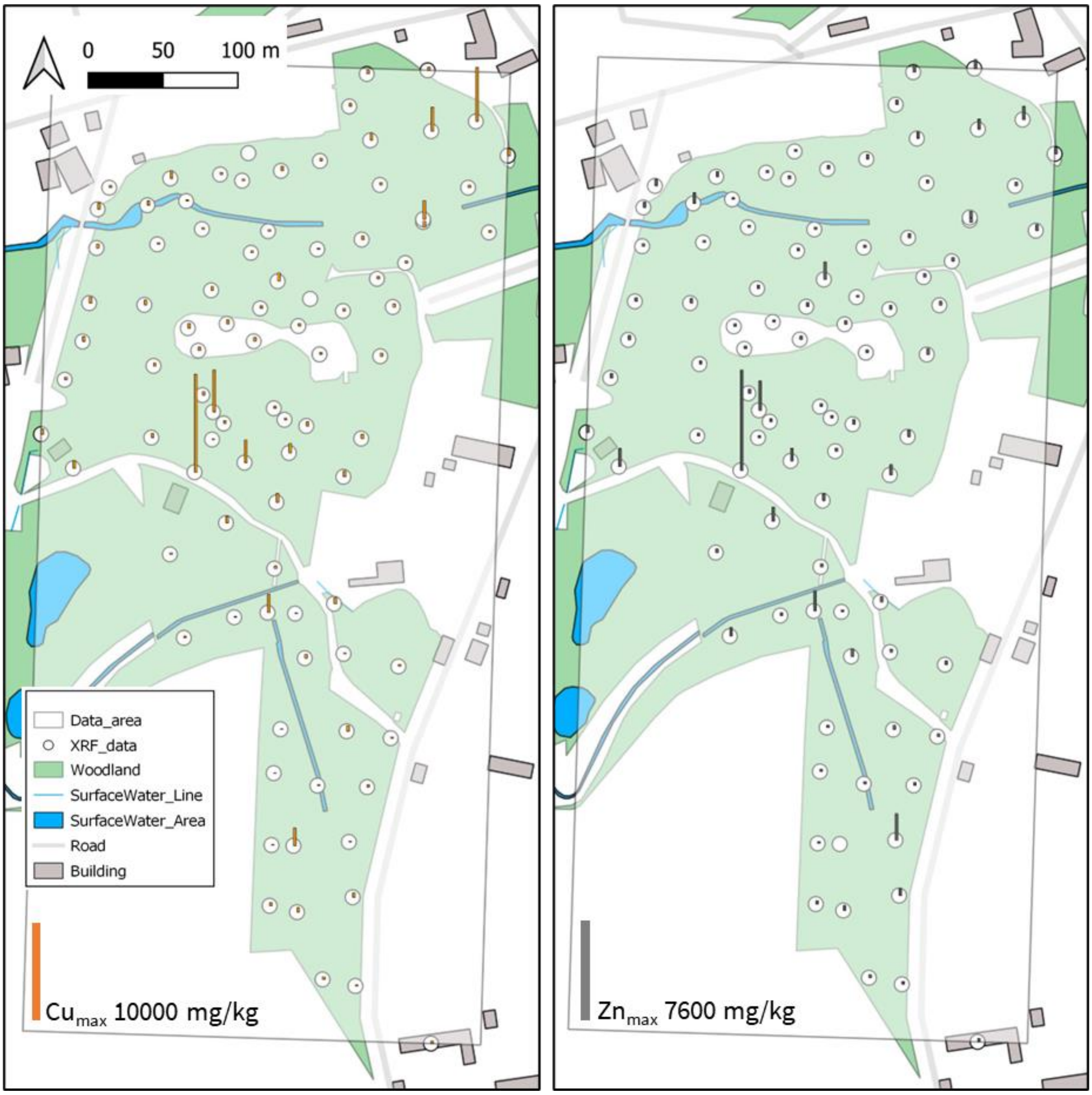

Figure 4-16 Spatial distribution of copper and zinc concentrations in mg/kg at NGC. The scale bar is the equivalent length of the maximum on site, which is shown next to it. Raw data courtesy of E. Ikhizama, University of Plymouth. Map base: OS OpenMap – Local, Open Government License © Crown copyright and database rights 2023 Ordnance Survey 100049047.

Figure 4-17 Spatial distribution of iron and arsenic concentrations in mg/kg at NGC. The scale bar is the equivalent length of the maximum on site, which is shown next to it. Raw data courtesy of E. Ikhizama, University of Plymouth. Map base: OS OpenMap – Local, Open Government License © Crown copyright and database rights 2023 Ordnance Survey 100049047.

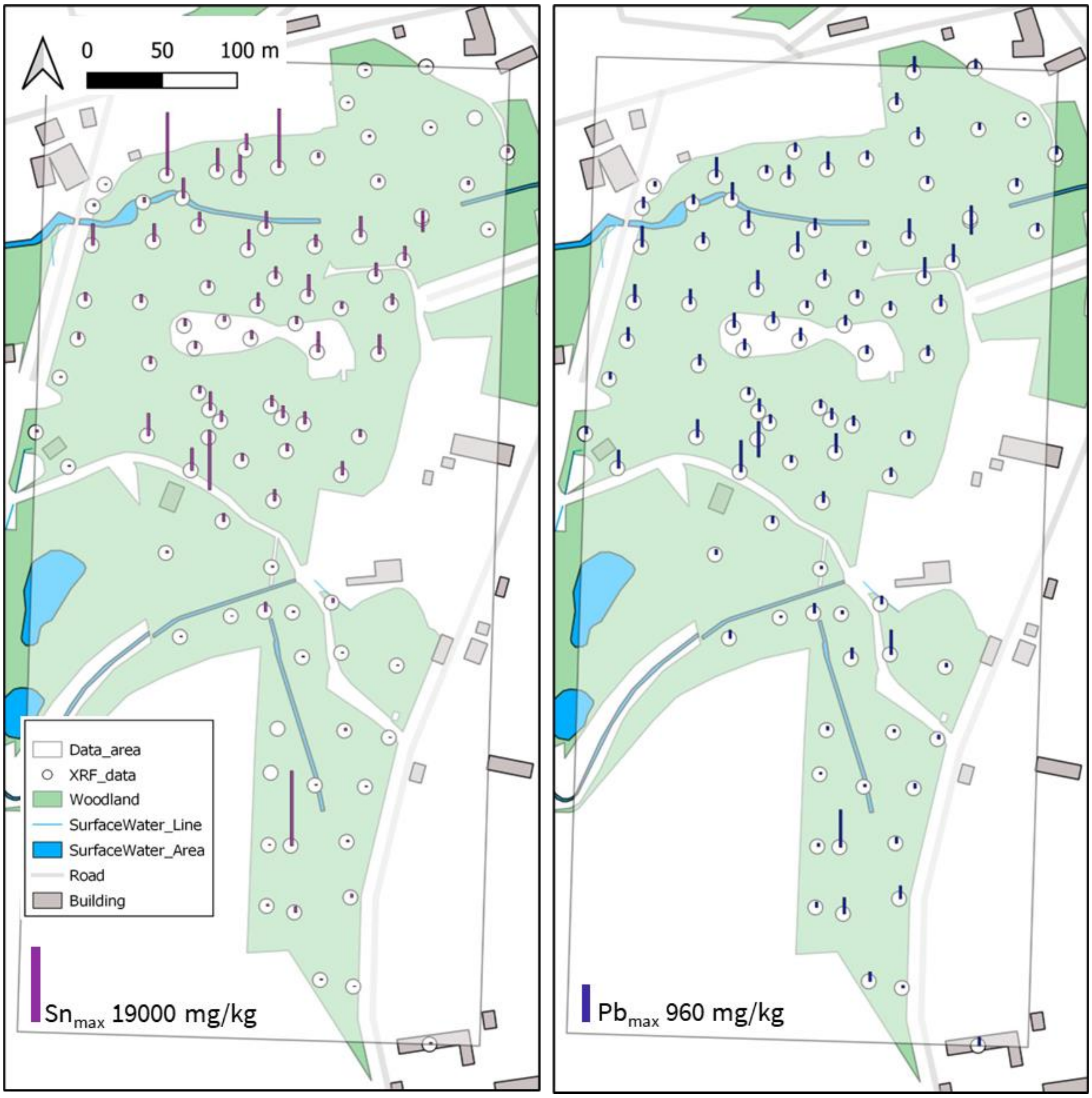

Figure 4-18 Spatial distribution of tin and lead concentrations in mg/kg at NGC. The scale bar is the equivalent length of the maximum on site, which is shown next to it. Raw data courtesy of E. Ikhizama, University of Plymouth. Map base: OS OpenMap – Local, [Open Government License](#) © Crown copyright and database rights 2023 Ordnance Survey 100049047.

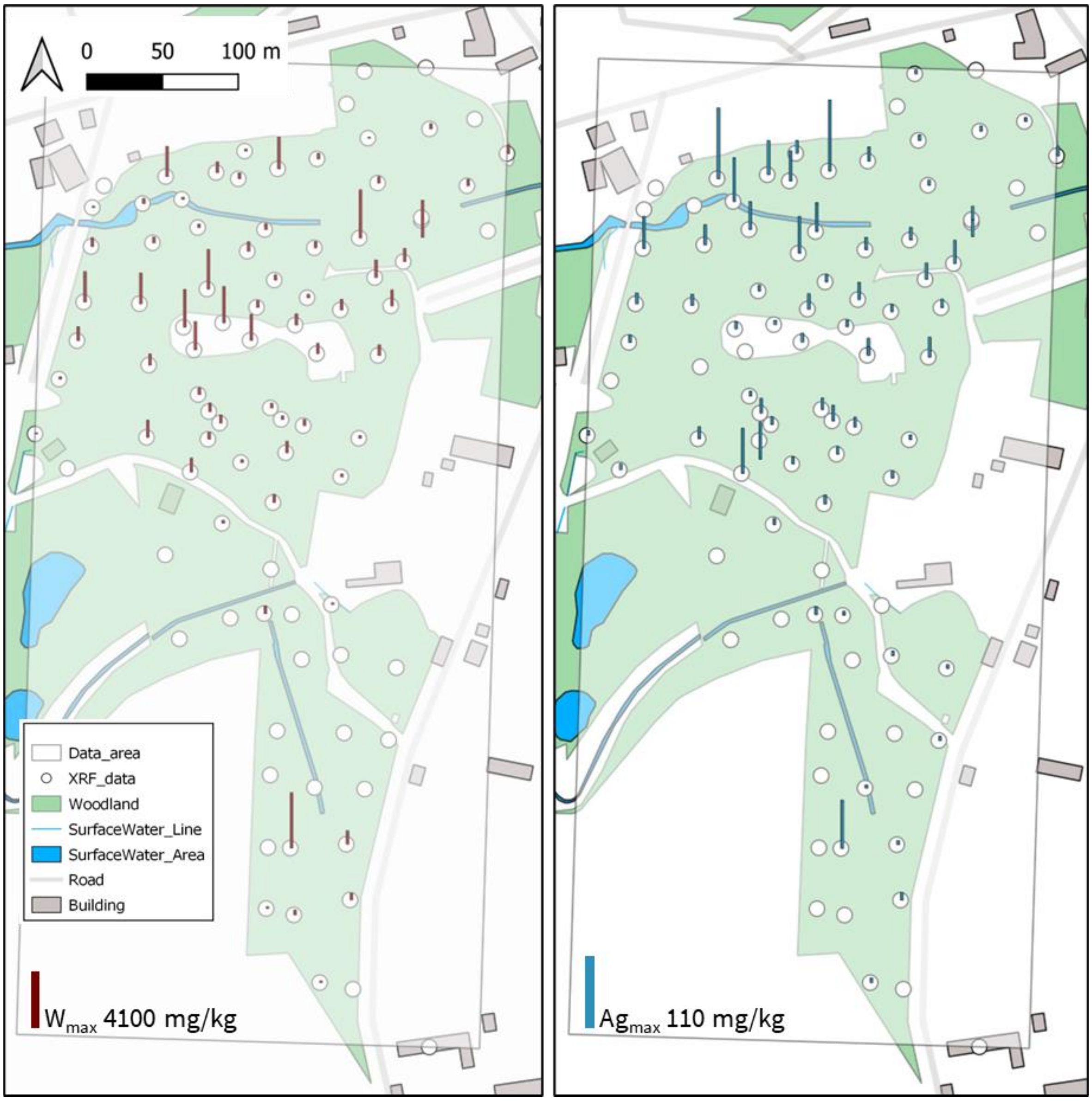

Figure 4-19 Spatial distribution of tungsten and silver concentrations in mg/kg at NGC. The scale bar is the equivalent length of the maximum on site, which is shown next to it. Raw data courtesy of E. Ikhizama, University of Plymouth. Map base: OS OpenMap – Local, [Open Government License](#) © Crown copyright and database rights 2023 Ordnance Survey 100049047.

4.5 Water Quality of Luckett Stream at Old Mill and Luckett (EA)

The Environment Agency (EA) undertook surveys of water quality between 13 August 2021 and 9 November 2022, collecting samples on 11 occasions each, at Old Mill (OM W in Figure 2-5) and at Luckett car park, downstream of New Great Consols mine site [47] (NGC W in Figure 2-5). Total metal concentrations were determined after acidification and dissolved concentrations after filtration. For the purpose of this report, particulate concentrations were calculated by subtraction of the dissolved from the total metal concentrations. The EA data set contains some points that indicate a need for a quality check. For example, the reported dissolved concentrations of Zn, Cu, Cd and Ni at Old Mill in March 2022 were higher than the total concentration, indicating either a loss in the total or contamination of the dissolved fraction of the sample. As the publicly available information does not allow quality assurance checks to be carried out, the data is presented and discussed here 'as given' and any quality issues may have affected the outcome of analyses presented here. Arsenic is not represented in the EA data and because lead was reported largely as Pb<2 µg/L, it is not included in this discussion.

The EA data indicate highly variable suspended matter (SPM) concentrations at both, Old Mill (10.1±6.2 mg/L SPM, Figure 4-20) and Luckett (9.3±10.0 mg/L SPM, Figure 4-21). The high spikes of SPM encountered in February 2022 are also present in the particulate Zn, Cu, Ni and Cd concentrations. However, with the exception of Ni at Old Mill, none of the particulate metal concentrations were strongly correlated (Pearson's, r>0.7) with SPM, suggesting that the SPM concentration was not the sole determinant of particulate metal fraction in this system. This implies different SPM sources, which in this catchment include agricultural run-off, legacy mining and septic systems as well as mine waste materials.

A comparison of time series at Old Mill (Figure 4-20) and Luckett (Figure 4-21) imply that the main sources of conductivity, nitrogen species (as oxidised nitrogen, NO3-N), reactive orthophosphate (as PO4-P), particulate nickel and dissolved iron lie upstream of Old Mill. Here, strong positive correlations between pH, conductivity, alkalinity, NO3-N, Mg and Ca concentrations imply an influence of bedrock and soil weathering on stream water chemistry in the upper catchment. Although the predominant geology in the vicinity is igneous (granite) and siliceous sedimentary (slate, chert) (Figure 2-2), carbonate (e.g. aragonite, cerussite, malachite, siderite) and phosphate (e.g. fluorapatite) minerals are recorded for the mine sites of this region in addition to the main sulfide ores (e.g. pyrite, arsenopyrite, chalcopyrite, galena, sphalerite) [21].

Strong negative correlations (r<-0.75) between conductivity and Zn, Cd and Cu concentrations at Old Mill indicate a source different from country rock for these metals, one that is associated with low pH (r<-0.70) and hence likely to be acid mine drainage (AMD). Likely candidates include Downgate mine, which has been classified by Turner [5] as 'very high risk' with respect to diffuse pollution (Figure 2-4) and Holmbush mine at the source of the southern branch of Luckett Stream (Figure 2-5). Mine workings and dumps at Downgate and Holmbush are reported to contain ores of copper, arsenic, tin, tungsten, antimony, iron, zinc, silver and lead, but not nickel [21], indicating that Ni is likely to be an uncommon, minor constituent.

The dissolved phase of Zn, Cu and Cd dominated at Old Mill and covaried closely with total concentrations (Figure 4-20), suggesting that leaching from spoil heaps and/or adit flow may be important sources of metals in the upper catchment. This may also be the case for Fe, for which the EA data only includes the dissolved phase.

Downstream of NGC, at Luckett car park, the mean dissolved and particulate concentrations for Cd, Zn and Cu were higher by factors of 1.5 - 2.6 than at Old Mill. This trend was also observed for dissolved metal/loids in the past (October and monthly surveys, Section 3.5), suggesting important contaminant sources occur between Old Mill and Luckett. Potential metal sources include not only the NGC site, but also the remains of Great Sheba Consols, Kelly Hole and Martha mines in the valley and Tom and Excelsior mines in Deerpark Stream.

Background dissolved iron concentrations were similar at both locations, as was the sharp peak concentration in October 2021. However, In March 2021 the second peak concentration at Old Mill did not translate through to Luckett car park, an unusual circumstance difficult to interpret. The Fe peak magnitudes were higher by factors of 3 - 4 in comparison to maxima reported in Section 3.5.

The particulate phase of Cu, Zn, Cd and Ni contributed significantly to the total metal concentration in samples with high suspended matter load (February, Figure 4-21), while at other times the dissolved phase dominated. Dissolved Zn, Cu and Cd, and separately particulate Zn, Cu and Cd co-varied, implying that either metal fraction undergoes common processes of mobilisation that are different for dissolved and particulate phases.

In contrast to contaminant metals, calcium and nutrient concentrations, conductivity and alkalinity were less variable and somewhat lower at Luckett than observed at Old Mill. The strong positive correlations (Pearson's >0.7) between alkalinity, phosphate, Mg and Ca indicate a catchment source for these parameters (see above), suggesting attenuation and/or dilution within the lower stream. A more detailed investigation would be required to identify processes and sources within the catchment.

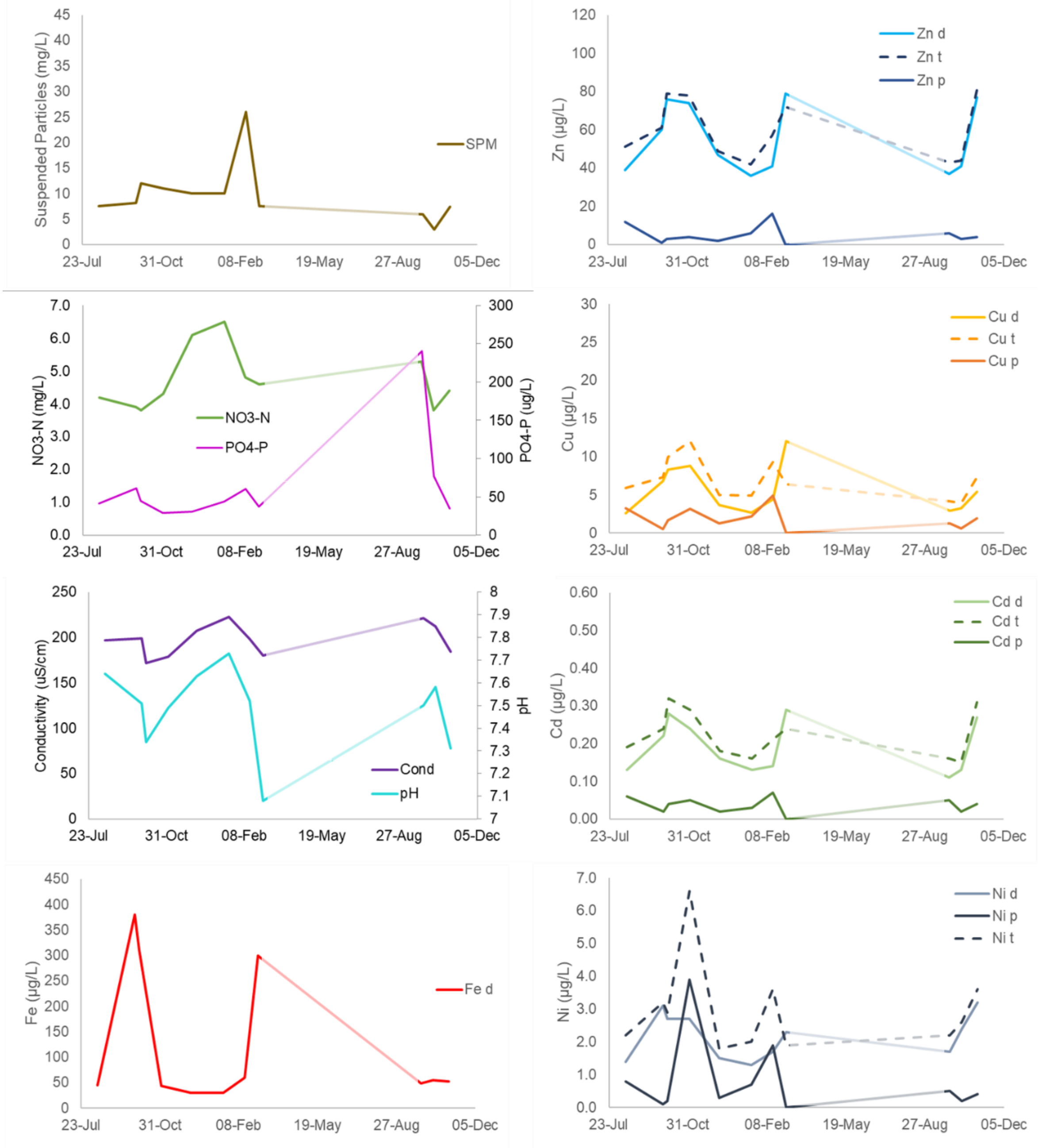

Figure 4-20 Old Mill: water quality parameters determined in 11 samples taken from Luckett Stream between 13 August 2021 and 9 November 2022 by the Environment Agency. Suffix d: dissolved, t: total, p: particulate (by subtraction). The line between March and September 2022 is faint to mark that the monthly sampling was interrupted between these dates and the connecting line is not an interpolation. Methodological detail and original data available at [47] under the Open Government License v3.0. © Crown Copyright.

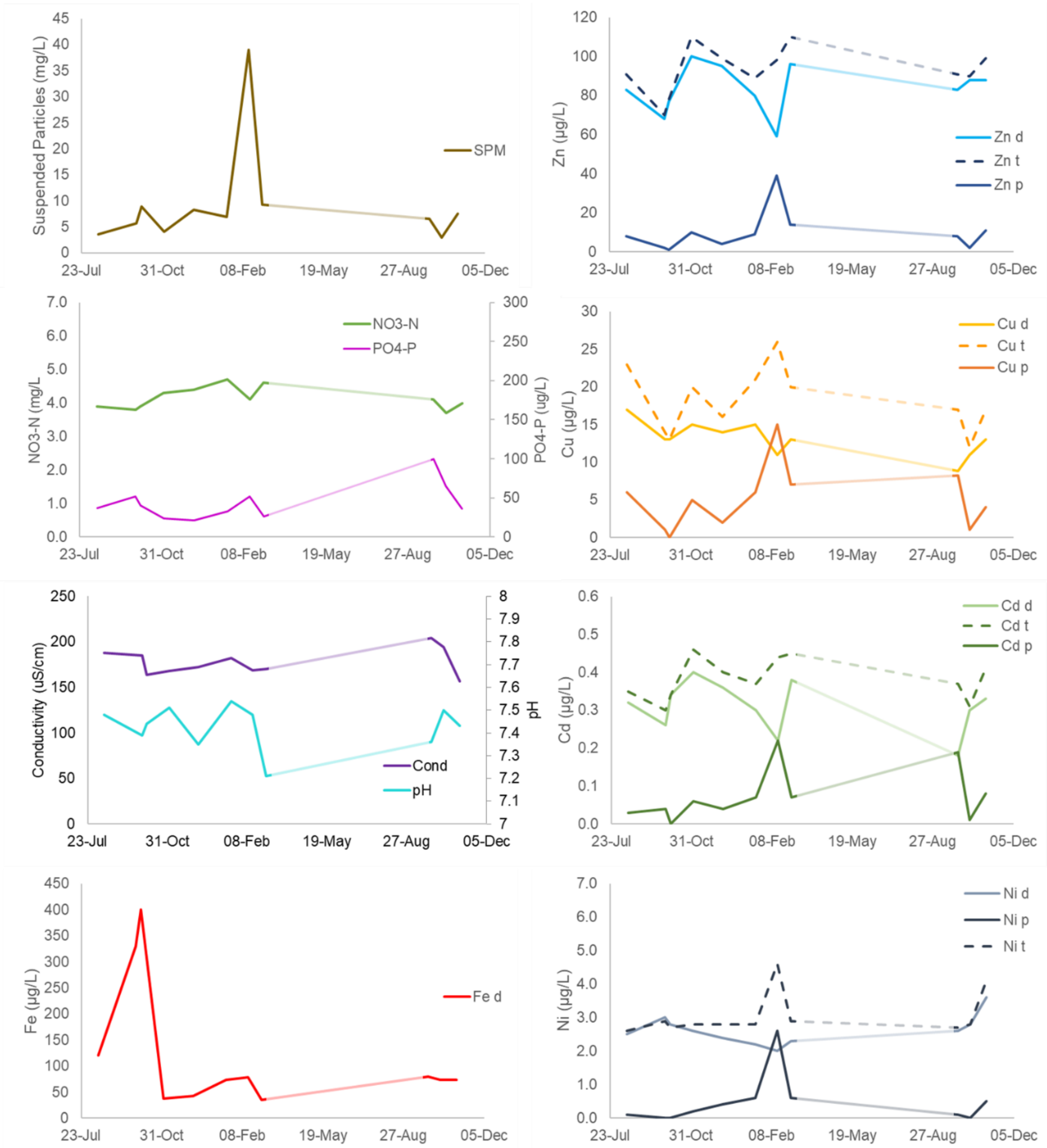

Figure 4-21 Luckett Car Park: water quality parameters determined in 11 samples taken downstream of New Great Consols Mine between 13 August 2021 and 1 November 2022 by the Environment Agency. Suffix d: dissolved, t: total, p: particulate (by subtraction). The line between March and September 2022 is faint to mark that the monthly sampling was interrupted between these dates and the connecting line is not an interpolation. Methodological detail and original data available at [47] under the Open Government License v3.0. © Crown Copyright.

Figure 4-22 compares dissolved and particulate Cu, Zn and Fe concentrations at Old Mill and Luckett car park from the EA surveys with archive data from the October and monthly surveys reported in more detail in Section 3.5.

In the more recent EA data set, the mean conductivity was higher by a factor of four (200±17 µS/cm at Old Mill, 180±14 µS/cm at Luckett), and the pH higher by 0.4 units (7.48±0.18 at OM, 7.43±0.09 at L). Dissolved Ca (17±1.6 mg/L at OM and 14±0.92 mg/L at L) and Mg (4.7±0.7 mg/L at OM and 4.4±0.53 mg/L) concentrations were consistent with the archive data.

Dissolved Cu and Zn concentrations were consistent between the October surveys and EA data at both, Old Mill and Luckett, whereby the October surveys exhibited a much larger variability of Zn at Luckett. Dissolved Cu concentrations obtained from monthly surveys in 2005/6 were significantly higher (ANOVA, $p<0.01$) than results from all other surveys. Particulate Cu and Zn concentrations at Luckett were similar in EA and monthly surveys.

Dissolved iron concentrations determined by the EA at Old Mill were significantly higher (ANOVA, $p<0.05$) than those determined during the October surveys, and more variable than those at Luckett. There was no significant difference between surveys in the mean Fe concentrations determined at Luckett at different times.

Overall, this comparison shows no indication of a distinct trend in either direction of concentrations in Luckett stream at Old Mill and Luckett car park over the period 2005 to end of 2022. Furthermore, the application of the Bio-Met Bioavailability Tool [43] to contemporary data confirms that the WFD Environmental Quality Standards (EQS) were still exceeded for Cu (local Cu HC5 = 6.6 µg/L) at Luckett (RCR 2.0) and for Zn (local Zn HC5 = 12 µg/L) at Luckett (RCR 7.0) and Old Mill (RCR 4.6). For a more detailed explanation of EQS, please refer to Section 3.7.2. In addition, the EQS for Cd (0.1 µg/L) was exceeded at both, Old Mill and Luckett.

This data comparison and the range of concentrations observed provides the insight that the sources of metal contamination in Luckett Stream have not changed significantly over the here considered time span (2005 to 2022). The contemporary EA data indicates that particulate matter could play an important role in carrying contaminants from mine waste into the stream during periods of high rainfall. In addition, there is a need to investigate diffuse and point sources of contamination in the Luckett Stream catchment in more detail.

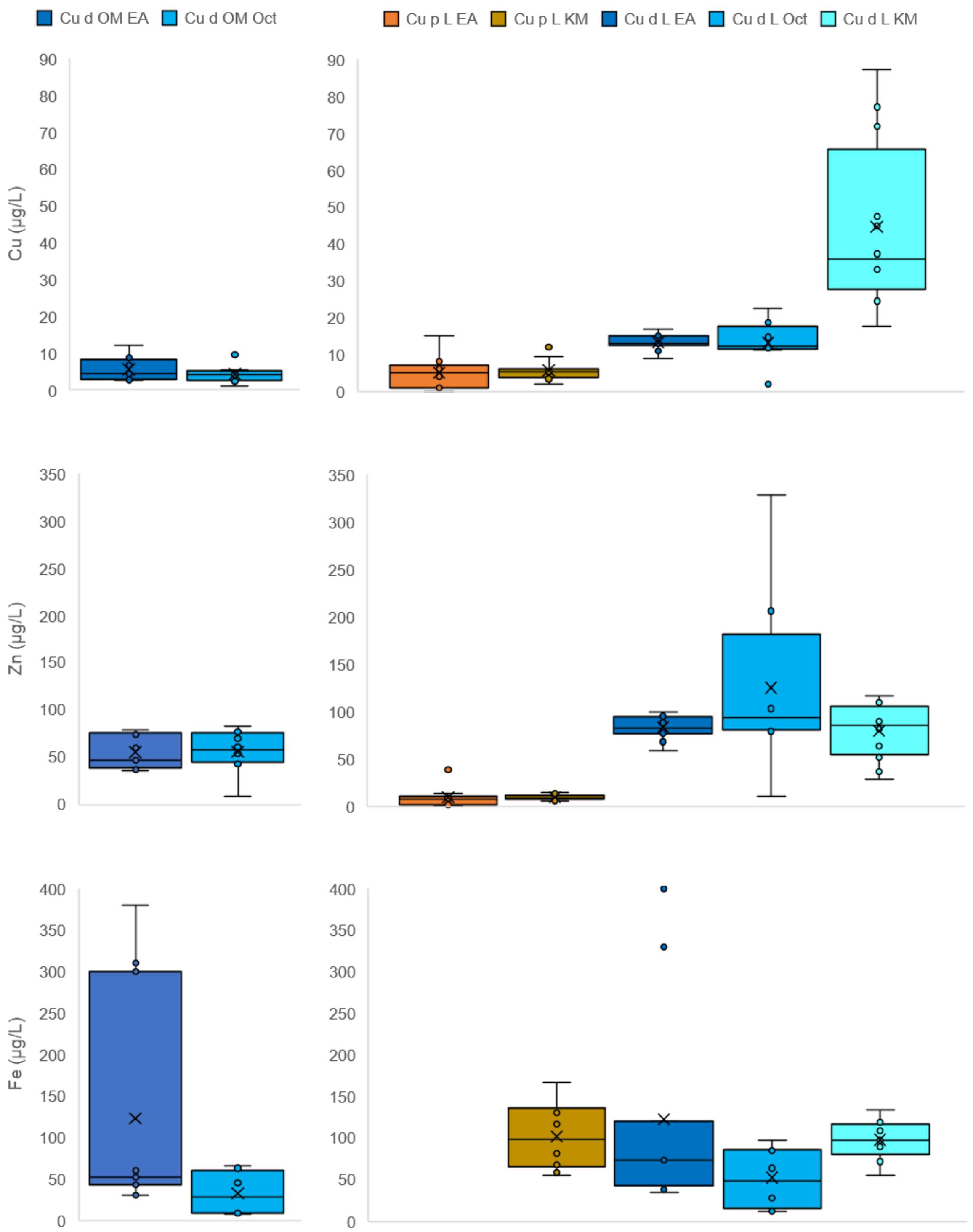

Figure 4-22 Box-and-Whisker plots comparing dissolved (d) and particulate (p) concentrations of Cu, Zn and Fe in the EA data (2021/22) with the October surveys (2008-2016, Oct) and monthly surveys (2005/6, KM) that were described in more detail in Section 3.5. OM – Old Mill, L – Luckett car park. EA data [47] available under the Open Government License v3.0. © Crown Copyright.

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4.6 Luckett Stream Catchment Survey

A detailed lower catchment survey was carried out in collaboration with the University of Plymouth with the aim to elucidate point and diffuse sources of contamination as well as identifying where attenuation and/or dilution occurs. The survey was undertaken within a period of high rainfall on 12 January 2023, when 13 water samples were collected between Old Mill and Luckett car park that included surface run-off from waste heaps and standing water on the NGC site (maps Figure 4-23 & Figure 4-24, photographs Figure 4-8 to Figure 4-4 & Figure 4-12).

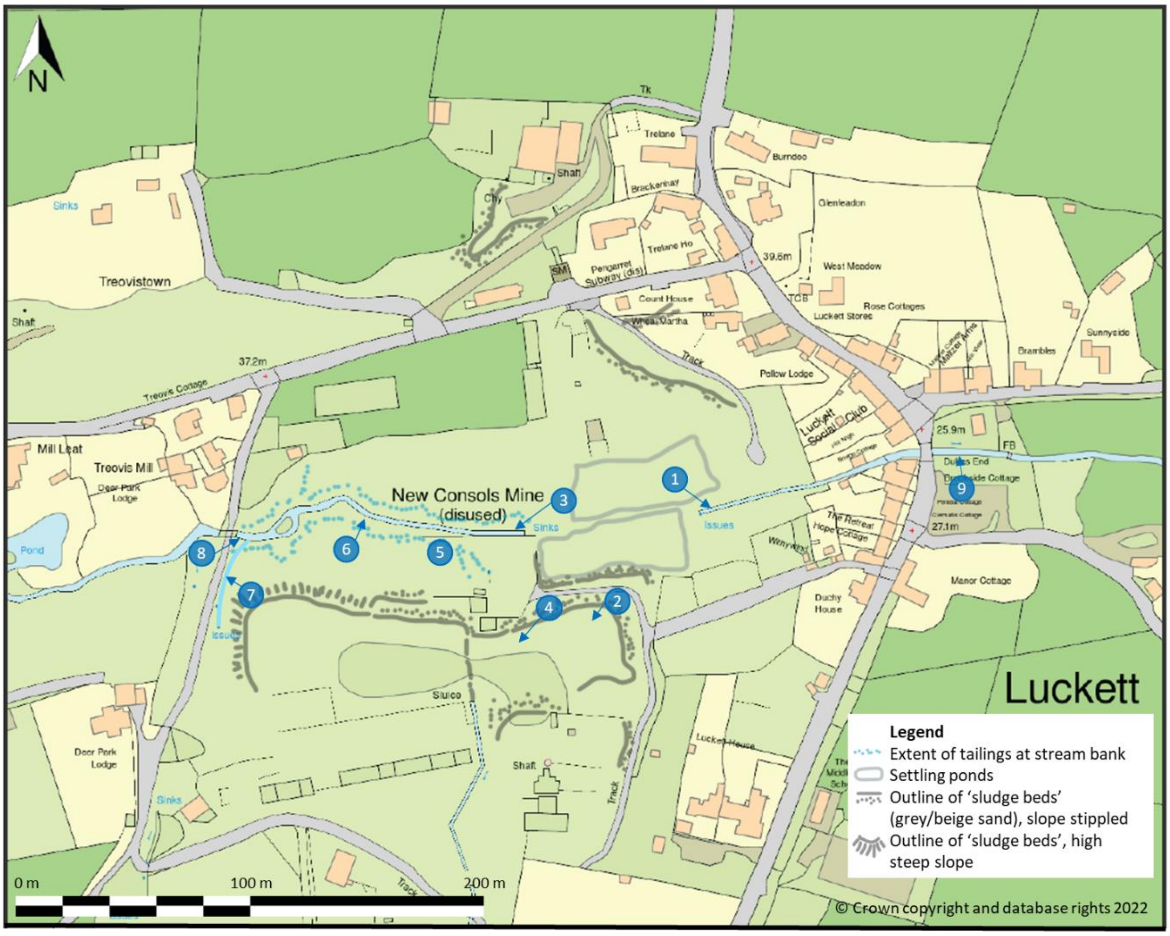

Figure 4-23 Northern part of New Great Consols Mine site showing sampling locations 1 to 9 of water taken on 12 January 2023. Hand-drawn annotations (see Legend) are approximate locations of surface features shown on a historic map from the 1950s, contemporary with the final ceasing of waste ore processing. Site Plan shows OSGridRef: SX38757351. Supplied by mapserve.co.uk a licensed Ordnance Survey partner (100053143). Map base © Crown copyright and database rights 2023 Ordnance Survey 100049047.

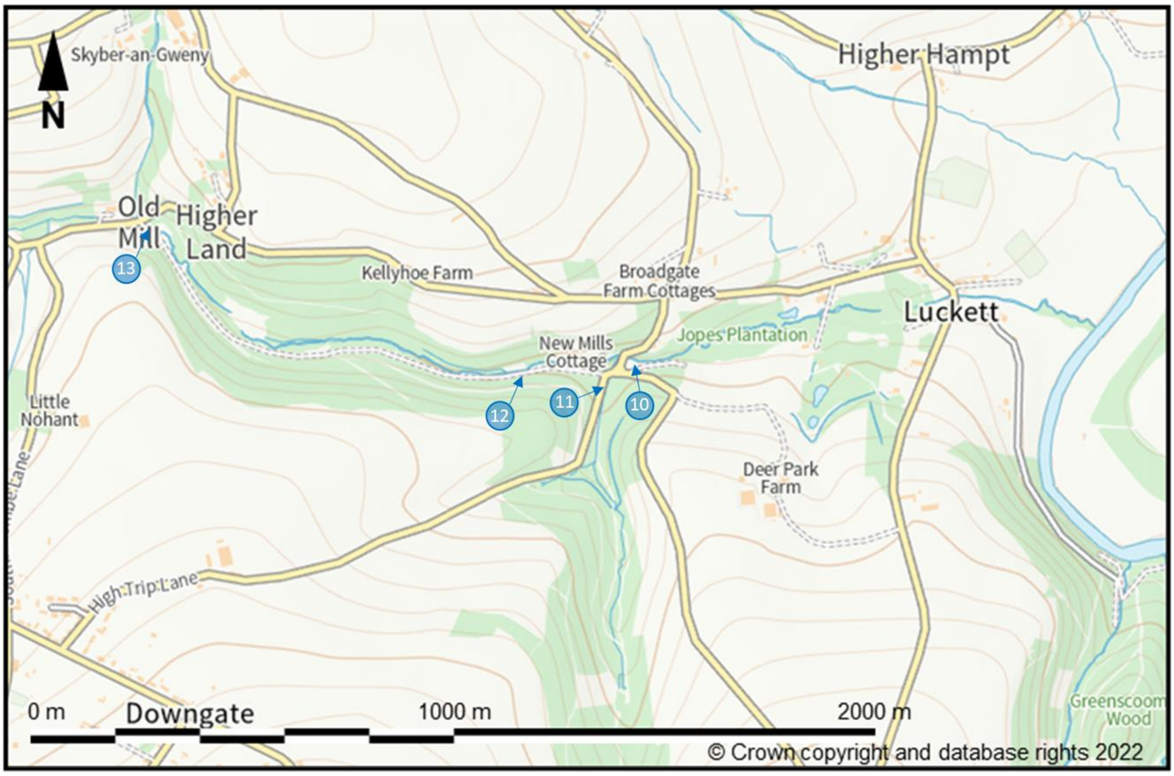

Figure 4-24 Catchment of Luckett Stream between Old Mill (west) to confluence with the Tamar (east) showing sampling locations 10 to13 of water taken on 12 January 2023. Map supplied by mapserve.co.uk a licensed Ordnance Survey partner (100053143). Map base © Crown copyright and database rights 2023 Ordnance Survey 100049047.

Temperature and pH were determined *in situ.* Within 24 h of collection, samples and three field blanks were sub-divided for a) conductivity measurements, b) nutrient analysis and c) filtration (45 µm) and acidification. Prepared samples and blanks were analysed for a suite of metal/loids using ICP-OES and for nutrients using segmented flow colourimetry.

The pH (6.98±0.48), nitrogen (nitrite + nitrate, 3.94±0.67 mg/L NO3-N) and reactive phosphate (40±26 µg/L PO4-P) concentrations in Luckett Stream between Old Mill and Luckett car park (Figure 4-25) were within the range observed in the EA data set discussed in Section 4.5. This was also the case for conductivity upstream of NGC. However, within the NGC site, conductivity increased sharply and then returned to background values at Luckett car park.

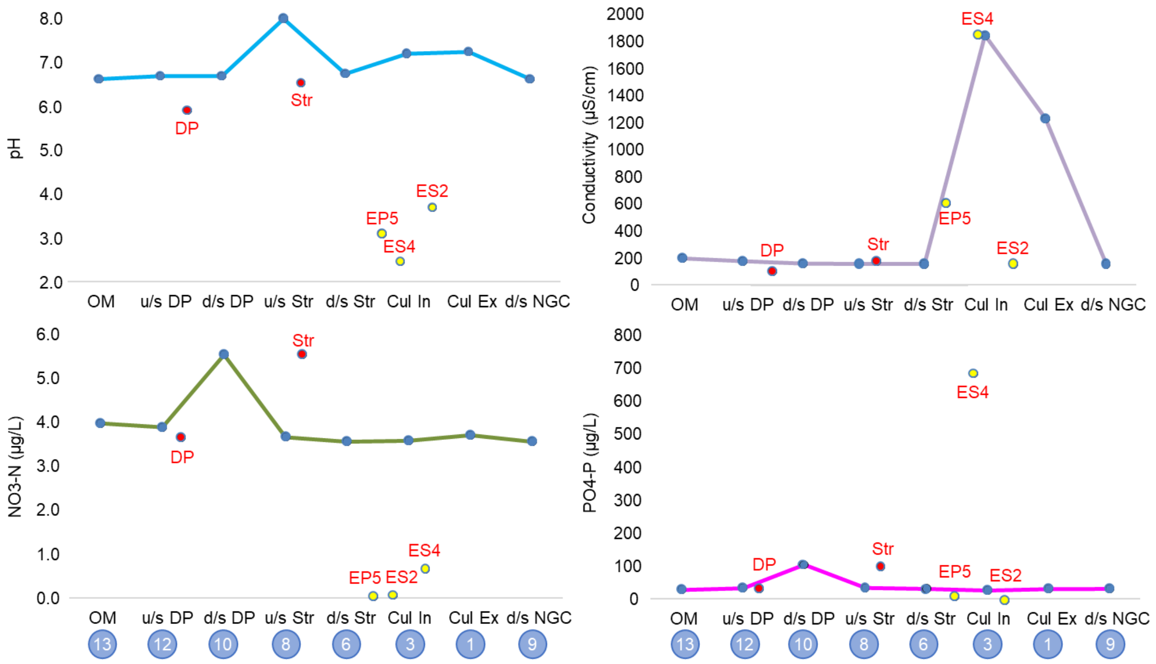

Figure 4-25 Luckett catchment: pH, conductivity, nitrate (NO3-N) and phosphate (PO4-P) (blue dots connected by lines), Deerpark Stream (red dot: DP), a small side stream upstream of NGC (red dot: Str), and in an ephemeral pond and two streams on NGC mine spoil (yellow dots: EP5, ES4, ES2). Labels on the x-axis are left to right following the stream from Old Mill (OM), upstream (u/s) and downstream (d/s) of DP, u/s and d/s of Str, inflow and exit of the culvert (Cul In and Cul Ex), and to Luckett car park (d/s NGC). Samples taken in tributaries (DP, Str) and ephemeral streams and the pond (EP5, ES4, ES2) are positioned along the axis at either their confluence with Luckett Stream or their longitudinal alignment with it. Blue sample points indicated along the lower axes refer to sites labels in Figure 4-23 & Figure 4-24.

Deerpark Stream (DP, sample 11 in Figure 4-24) featured somewhat lower pH and similar conductivity and nutrient concentrations to Luckett Stream but appeared to have little influence on those parameters downstream of the confluence. In archive data (October surveys, Section 3.5) the ratio of stream flow in Deerpark Stream to Luckett Stream at Old Mill ranged between 0.11 to 0.43, indicating substantial inputs at times, but water flow rates were not determined during this current catchment survey. The increase in nutrient concentrations around the confluence with DP may be associated with additional inputs from agricultural land or septic tanks of cottages on the northern bank of Luckett Stream.

Substantially less voluminous than DP, the small side stream (Str, sample 7 in Figure 4-23) arises on the upstream boundary of the main NGC site next to a track leading up to Deer Park Lodge. Slightly elevated nutrient concentrations in this sample (Figure 4-25) suggest a domestic or agricultural origin of this water course.

The ephemeral pond (EP5, sample 5 in Figure 4-23) formed from pooled rainwater and mine waste drainage in a compacted and largely unvegetated area of whitish mine tailings on the southern bank of Luckett Stream. Among obvious inflows were trickles from a waste dump and along a footpath from the east, and it overflowed through a row of shrubs into the Luckett Stream. While sampling EP5, sediment was readily mobilised, potentially adding to the particulate metal load. The water was characterised by low nutrient concentrations, high conductivity (605 µS/cm) and a substantially lower pH (3.1) than in Luckett Stream (Figure 4-25).

The two ephemeral streams (ES4 & ES2, samples 4 and 2 in Figure 4-23) arising on the base of mine spoil heaps illustrate the heterogeneity of acid mine drainage and the mine waste they originated from at NGC. ES4 had the lowest pH (2.5) and highest conductivity (1850 µS/cm) and PO4-P (684 µg/L) concentrations of any water sample analysed at that site at any time, while ES2 was remarkable for its low pH (3.7, Figure 4-25) and, true also for EP5 and ES4, its highly elevated metal/loid concentrations (Figure 4-26) discussed in more detail below.

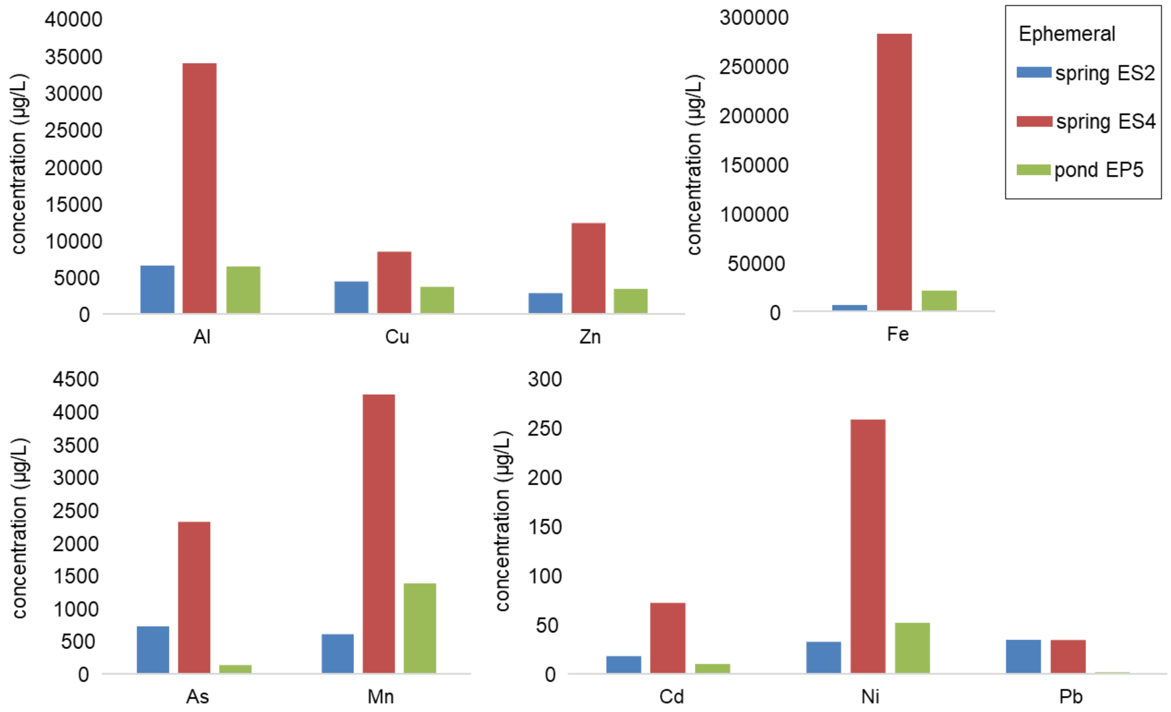

Figure 4-26 Metal/loid concentrations in acid mine drainage sampled from two ephemeral springs (ES2, ES4) and a pond (EP5) on NGC. Also refer to photographs in Figure 4-5 & Figure 4-7.

Metal/loid profiles along Luckett Stream (Figure 4-27) exhibited highly variable profiles during this high flow survey. Upstream of NGC, metal/loid concentrations were generally in the range of data reported for Old Mill in previous sections.

Aluminium, iron and manganese concentrations upstream of NGC were elevated above what can be considered background for the whole Tamar freshwater catchment (G-Base data median: 7.8 µg/L Al, 0.21 µg/L Fe, 0.037 µg/L Mn [13]). Within the NGC site, in the short distance between sample 6 and 3 (Figure 4-23), the concentrations of Al, Fe and Mn increased with conductivity (Pearson's correlation r>0.9) by approximately one order of magnitude. Both, the overflow of EP5 and ephemeral ES4 lie within this stretch as potential sources of AMD, and to the north of the stream was another ephemeral pond surrounded by red mine tailings (Figure 4-16 - Figure 4-19).

A qualitative indicator of substantial run-off and/or sediment mobilisation was the higher turbidity at this site, elevated above the generally high suspended matter load in Luckett Stream at all sampling sites on that day. In addition, AMD in form of leachate and adit seepage may have entered the hyporheic zone directly. Further downstream within the culvert and beyond, metal profiles imply dilution and/or attenuation for Al, Fe and Mn, along with conductivity, all reaching similar or slightly higher values to those observed at Old Mill at the most downstream site at Luckett car park (Sample 9 in Figure 4-23).

The concentration of other metal/loids, including arsenic, copper and zinc (Figure 4-27), as well as antimony and nickel (<10-31 µg/L Sb and <2.0-6.6 µg/L Ni, data not shown) suggest strong sources of AMD in the upper reaches, as well as multiple points of additional inputs, dilution and/or attenuation downstream of Old Mill. The Tamar catchment median concentrations for these metals determined by the BGS were 0.7 µg/L As, 1.0 µg/L Cu, 2.8 µg/L Ni, 0.08 µg/L Sb and 2.0 µg/L Zn [13].

Distinct increases in dissolved As, Cu and Zn between Old Mill and upstream of the confluence with Deerpark Stream imply that diffuse sources of these metals are present within that stretch of the catchment, likely to be associated with Great Sheba Consols and Kelly Hole mines (Figure 2-5). At DP dilution and/or attenuation occurs for As, Cu and Zn, followed by an increase in their concentrations and further decrease within NGC to d/s Str (Sample 6 in Figure 4-23).

Although the pH and concentrations of Zn, As and Cu in the small side stream (Str) were lower than in Luckett Stream, its comparatively low flow suggests that processes, other than dilution by Str, may be responsible for the sharp decline of pH, As and Cu downstream of the confluence. These may include the removal from solution through precipitation or co-precipitation as a result of mixing with waters of different chemistry, although this is not verifiable with the available data.

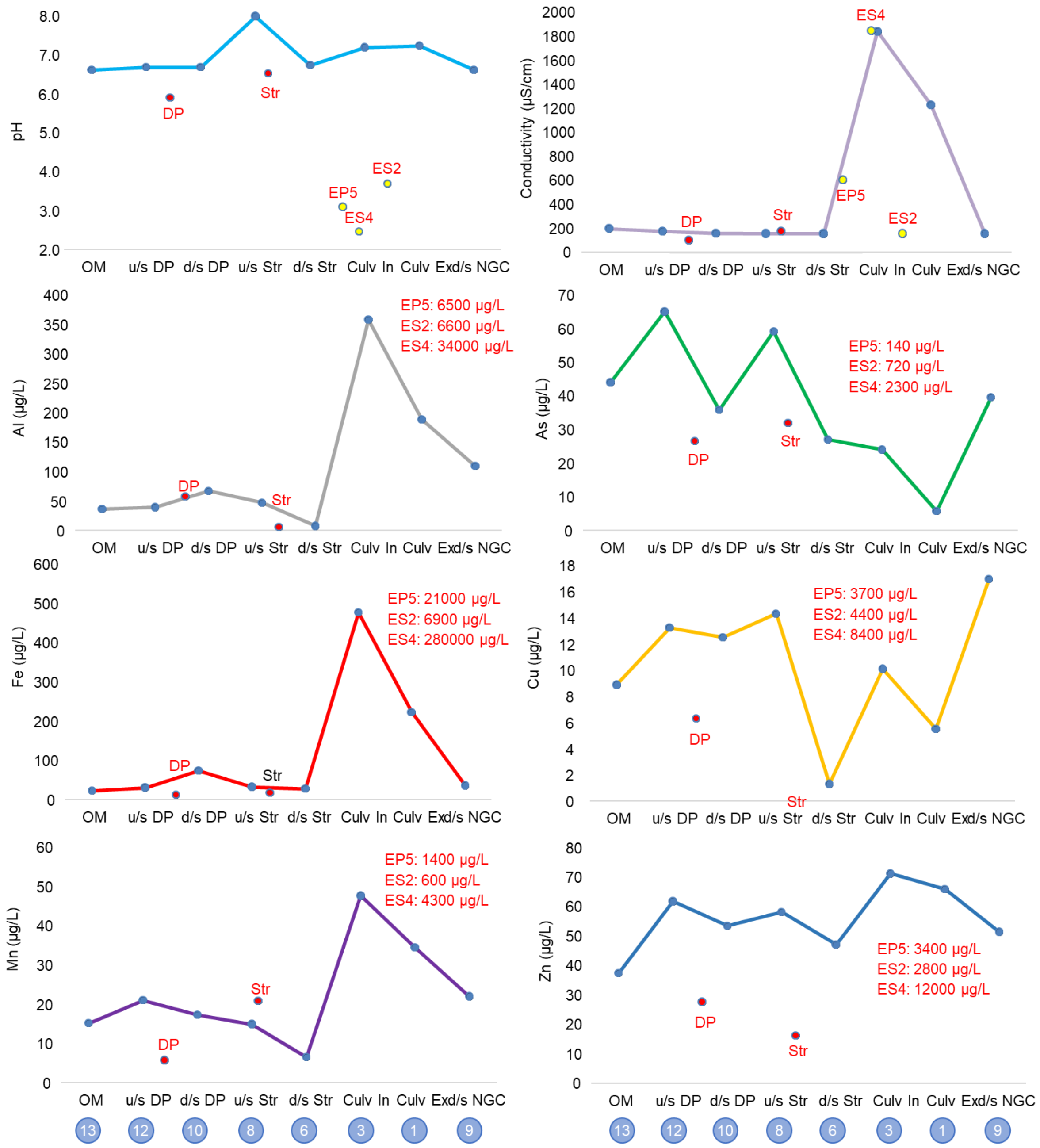

Figure 4-27 Luckett catchment: metal/loid concentrations in Luckett Stream (dots connected by line), Deerpark Stream (red dot: DP), a small side stream upstream of NGC (red dot: Str). Concentrations in an ephemeral pond and two streams on NGC mine spoil (EP5, ES4, ES2) provided in red writing as they are far beyond the scale of the y axis. Labels on the x-axis and abbreviations: see caption to Figure 4-25. Conductivity and pH included for easy comparison.

Further downstream, clear inputs of Cu and Zn occur with an increase of conductivity alongside the sharp rises in Al, Fe and Mn concentrations and this may be associated with AMD sources in that region, including EP5 overflow, overflow from an ephemeral pond on the northern bank (located between the positions of sample 6 and EP5), AMD of similar characteristics to ES4 and ES2, as well as leachate reaching the hyporheic zone. In contrast, dissolved arsenic continued to decrease throughout the NGC site towards the culvert exit.

Of particular interest are the differences in metal concentration between the inflow and exit of the culvert. The scheduling documentation of Historic England mentions an adit discharge into Luckett Stream within the culvert [20]. The profiles shown in Figure 4-30 suggest that water inputs of low conductivity, Al, Fe, Mn, As, Cu and Zn reaches the stream between the inflow and exit of the culvert. Whether this is water entering via an adit, diffuse groundwater flow or a buried drainage pipe remains uncertain.

Further downstream, sharp increases of As and Cu concentrations and slight lowering of pH suggest more contaminated run-off and/or sub-soil flows reach the stream between the culvert exit and Luckett car park. This stretch is relatively inaccessible because of a bramble thicket and the site boundary with private gardens. Historic maps from the 1950s indicate a range of shafts, mine waste dumps and a chimney upslope to the north, as well as settling ponds and tailings on both sides of the stream (Figure 4-23). The walkover surveys identified level changes on the ground with a likely drainage direction towards the stream downstream of the culvert, as well as ephemeral spring flow from the north into a low-lying boggy area. In addition, visual inspection showed that reddish-brown tailings form at least some of the stream banks are located downstream of the culvert (Figure 4-9). Any of these features is a potential source of acid mine drainage to the stream.

4.7 Discussion

In this section, observations made during walkover surveys were presented and compared with evidence collected in 2005/6. The range of potential sources and pathways of contamination known from earlier visits to the site, namely the calciner complex, mine waste dumps and erosion, remain largely unaltered. However, the process of natural revegetation has resulted in a more extensive cover of tailings in the valley bottom, and this affords some protection from physical erosion in those areas. Nevertheless, many of the steeper slopes of waste dumps and tailings and some level areas of mine waste remain barren as a result of erosion and compaction and are at risk of exporting highly contaminated material and acid mine drainage to the stream.

The vegetation present on the waste dumps and other highly contaminated ground is resilient to the challenging conditions of the substrate: high metal, acidic, low nutrients and sub-optimal water retention conditions that are either to freely draining or water-logged. Adaptations to these conditions include:

- lichens are fungi and independent of substrate composition because they rely on a symbiosis with photosynthesising algae or bacteria for their carbon source and obtain water and nutrients from the atmosphere,
- tolerance of periodic desiccation (e.g. mosses, gorse),
- tolerance of waterlogging (e.g. shallow-rooted trees, such as birch, heather, mosses),
- leguminous plants that fix nitrogen from the air and store it in root nodules, therefore are not dependent on soil nitrogen sources (e.g. gorse),
- tolerance to low nutrient concentrations (e.g. lichens, mosses, grasses),
- tolerance to acid soils (e.g. heather, common bent grass),
- tolerance to metal/loid contamination (e.g. lichens, some mosses, common bent grass, a range of annual plants),
- plants that evade inhospitable conditions by connection to the parent plant growing at a distance in more favourable soils (e.g. bramble, ivy).

The presence of organisms featuring such strategies and adaptations is worth recording in the context of the site for consideration in nature-based remediation solutions.

In this context, the analysis of 94 soil and mine waste samples across the NGC site afforded the identification of zones upon which remedial interventions may be focused. The spatial analysis presented with Figure 4-28 was carried out for metal/loids with high or moderate enrichment factors (EF) with respect to the UK average (EF_{Cu} = 33, EF_{As}=697,

EF_{Zn}=6.3, EF_{Sn}=716) and highlights hotspots and areas where concentrations are in the upper quartile for surface soil concentrations at NGC. In summary, south to north:

- highest As, Cu and Sn levels on site in a sample of a small, shallow, finely grained, off-white mine waste deposit (sample S7, Figure 4-14) in the south of the site,
- arsenic and a hotspot of Zn in the area surrounding the remains of processing facilities, buildings and elevated ground in the south,
- copper hotspot south of the path into the south of the site (sample S102),
- Zn and Cu in the soil near the arsenic calciner chimney (sample S104),
- As, Sn, Cu and Zn in the central area surrounding the calciners, extending west (Cu, Zn) to remains of a building and the site boundary and path,
  east (Cu, Zn, Sn) to encompass a set of buildings and mine spoil,
  south (Cu, Zn, As, Sn) to the track and beyond the arsenic mill,
- Cu, As and Sn in the area of coarsely grained mine waste dumps with steep slopes facing north,
- As and Sn (with areas of Cu) in the finely grained, off-white deposits south of the stream,
- As and Sn in the finely grained, red and off-white deposits north of the stream,
- Zn and Cu in the northeast, encompassing the track, engine house, and ground leading up to the Miner's Dry and Wheal Martha.

Figure 4-28 Site plan highlighting areas of Cu, Zn, As and Sn concentrations in the upper quartile of 94 surface soil and mine spoil samples obtained on NGC during May and June 2023 (full data displayed in Figure 4-16 to Figure 4-19). Map base supplied by mapserve.co.uk a licensed Ordnance Survey partner (100053143). © Crown copyright and database rights 2023 Ordnance Survey 100049047.

Contemporary water quality data collected by the EA in 2021 and 2022 was analysed and followed up with a more detailed catchment survey between Old Mill and Luckett car park. These recent data show no evidence of an abatement of contamination in Luckett Stream and confirm that the mining and agricultural activities in the catchment upstream of Old Mill have a substantial impact of water quality entering the valley at Old Mill.

Two distinct sources of suspended particles and water composition have been identified, one related to agriculture and characterised by high nutrient, conductivity, alkalinity and calcium/magnesium concentrations, the other impacted by acid mine drainage in the upper catchment (Holmbush, Downgate).

It is important to note that metal/loid concentrations were above the catchment background at Old Mill, with important inputs of As, Cu and Zn occurring between OM and NGC. The insights from the analysis of archive and contemporary data are captured in a schematic representation of the potential influences on water quality in the Luckett Stream catchment (Figure 4-29).

Within the boundaries of the New Great Consols site, different mineralogy of mine workings and waste deposits from a variety of metallurgical processes resulted in a legacy of heterogeneous materials, which are exposed to physical and chemical weathering, as well as biologically mediated oxidation. Hereby, iron and arsenic have been shown to be present mainly in the oxidisable fraction and hence relatively mobile within the environment (Section 3.4). Although archive data suggests much lower mobility of Cu and Zn in the mine waste, their high overall concentration in solids, as well as potentially different mobilities in wastes beneath the surface, resulted in high metal concentrations in AMD leachate on the site, as observed in ephemeral pond and streams (Figure 4-26).

The contemporary catchment survey was undertaken after a period of prolonged rainfall and longitudinal studies (monthly surveys in Section 3.5 and EA data in Section 4.5) suggest that the contamination in Luckett Stream peaks during winter months. Surface run-off, AMD and bank erosion are obvious sources and pathways in winter, which may be less prevalent in dryer and less energetic conditions. However, contamination still occurs during spring, summer and autumn and sub-surface processes, such as leachate generation at the interface with shallow ground water may dominate inputs during dry periods.

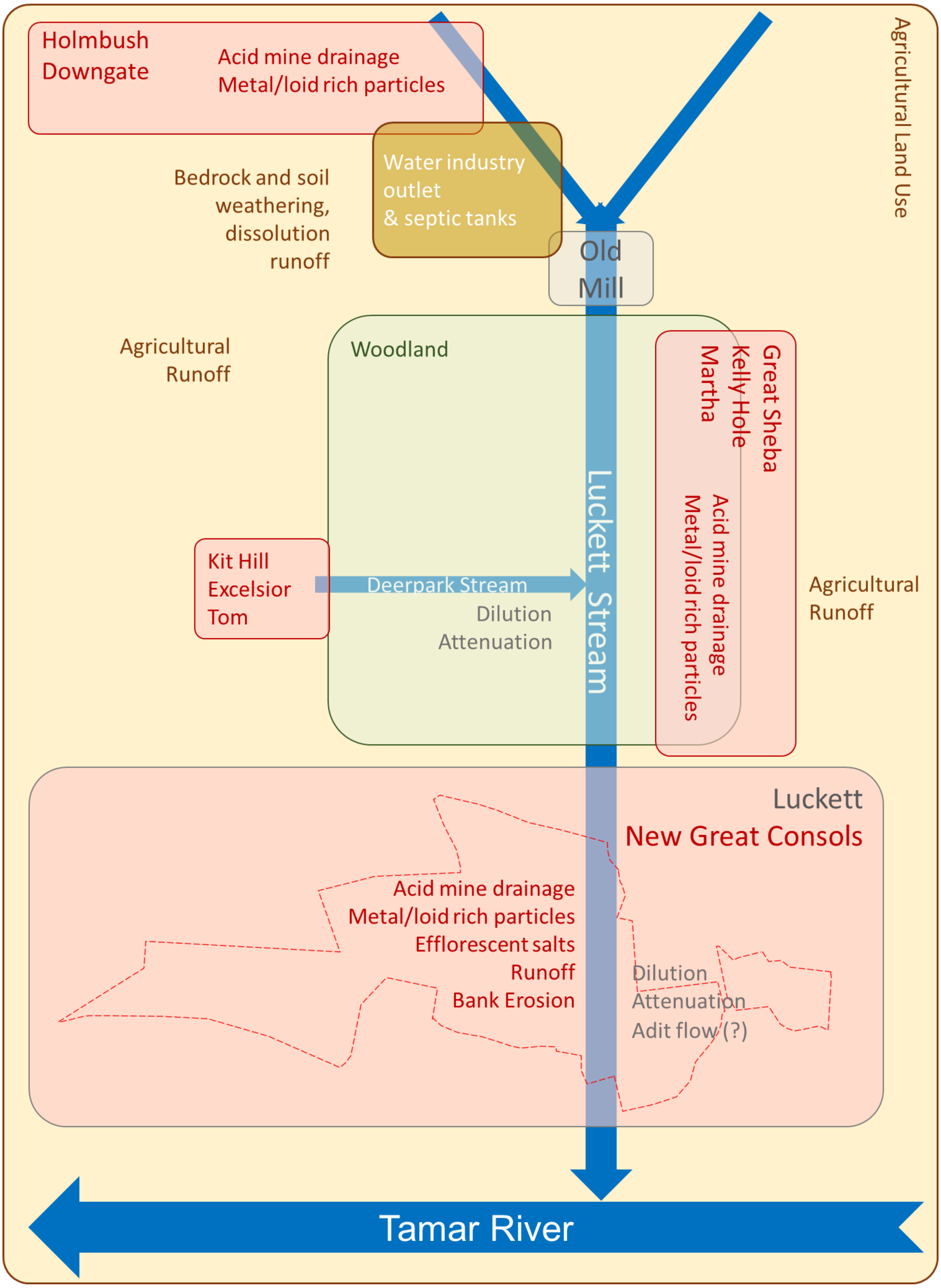

Figure 4-29 Schematic of the Luckett Stream catchment, showing potential influences on the stream water quality from habitation, land use and legacy mines.

In summary, the seasonality of contamination in the stream suggests that changes in rainfall, temperature and wind affect a variety of processes, including:

- the intensity of aeolian (wind-blown) dispersion of solids,
- surface processes, such as rain pitting, freeze-thaw erosion, gully erosion, slope failure caused by hydraulic pressure,
- the chemical and biological leaching of contaminated solids, dependent on temperature-dependent kinetics and microbial activity,
- the formation and dissolution of efflorescent salts, dependent on wetting/drying cycles and water ingress,
- AMD transport via surface run-off, shallow groundwater, deep groundwater, adit flow,
- the kinetics of geochemical cycling of contaminants within soils, mine spoil and tailings, stream sediment,
- dilution of metal concentrations in the stream by surface run-off from Luckett village, woodland and agricultural land,
- biological activity, such as microbial, plant uptake, biomagnification, recreation and footfall with dispersal of contamination.

The annotated map of NGC (Figure 4-30) summarises the main sources and pathways of contamination identified at the centre of the site. Combined with the knowledge gained from the high resolution surface soil and spoil analysis across the whole site (Figure 4-31), the outcomes of this section form the basis of developing specific remediation strategies. While this is the topic of Section 5, Figure 4-30 clearly points towards prioritising efforts to reduce:

- fluvial erosion and run-off from tailings (As, Sn, Cu) to the north and south of Luckett stream,
- aeolian and gravitational erosion, water ingress and fluvial transport from coarsely grained mine spoil dumps that occupy the area from the south of tailings to the calciners (As, Cu, Sn),
- generation and leaching of efflorescent salts from calciners and calciner chimney,
- water ingress, leaching and run-off from the central site (As, Cu, Sn, Zn) encompassing the calciners and extending to their east and west, as well as south of the arsenic mill,
- water ingress, leaching, run-off and aeolian erosion from the small, isolated waste heap (sample 7).

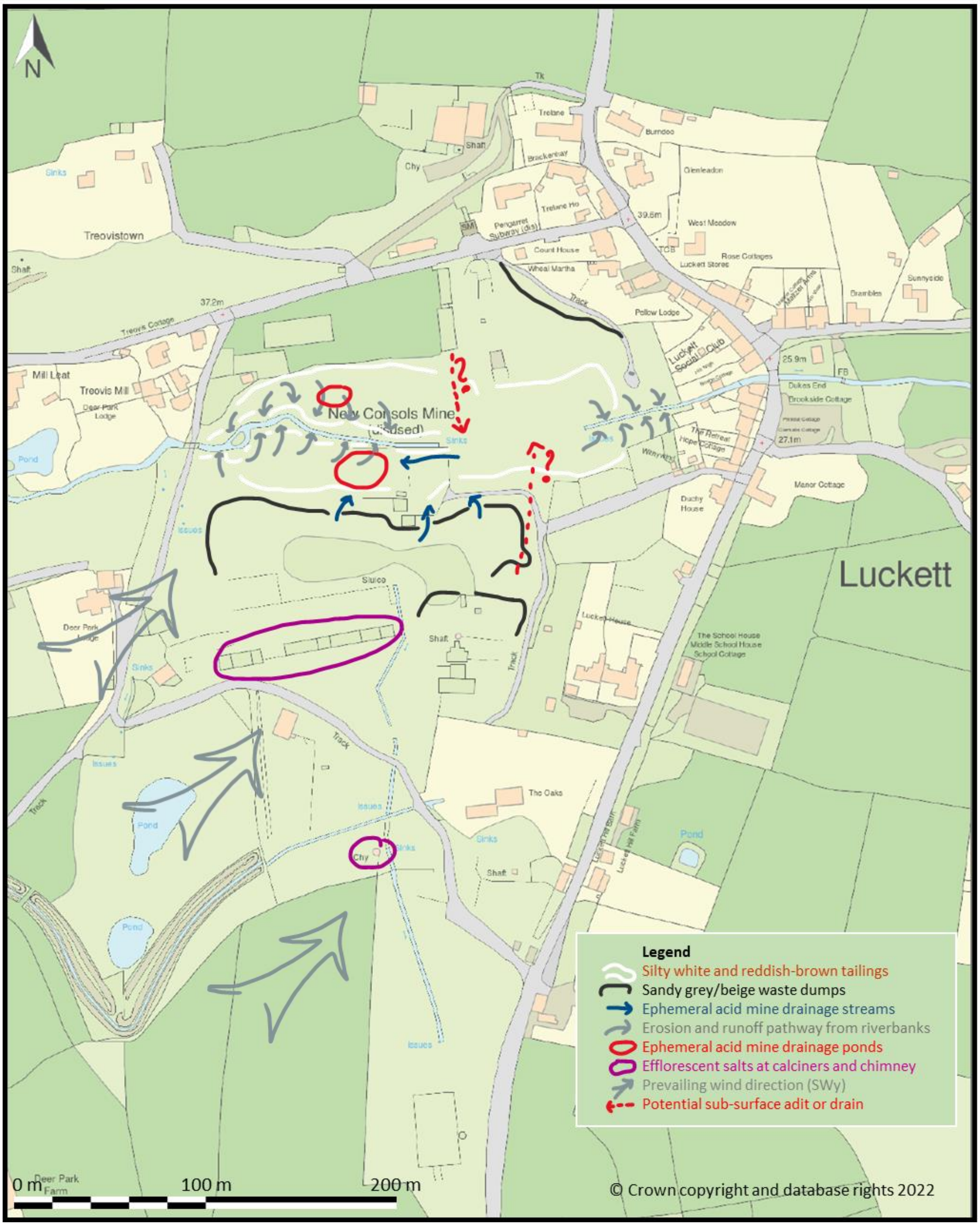

Figure 4-30 Main sources and pathways of contamination to the stream. Route of calciner flue to chimney is uncertain and not marked. Outline of tailings (white) and waste dumps (black) are approximate. The presence or route of subsurface adits or drains is unknown. Map base as for Figure 4-28 © Crown copyright and database rights 2023 Ordnance Survey 100049047.

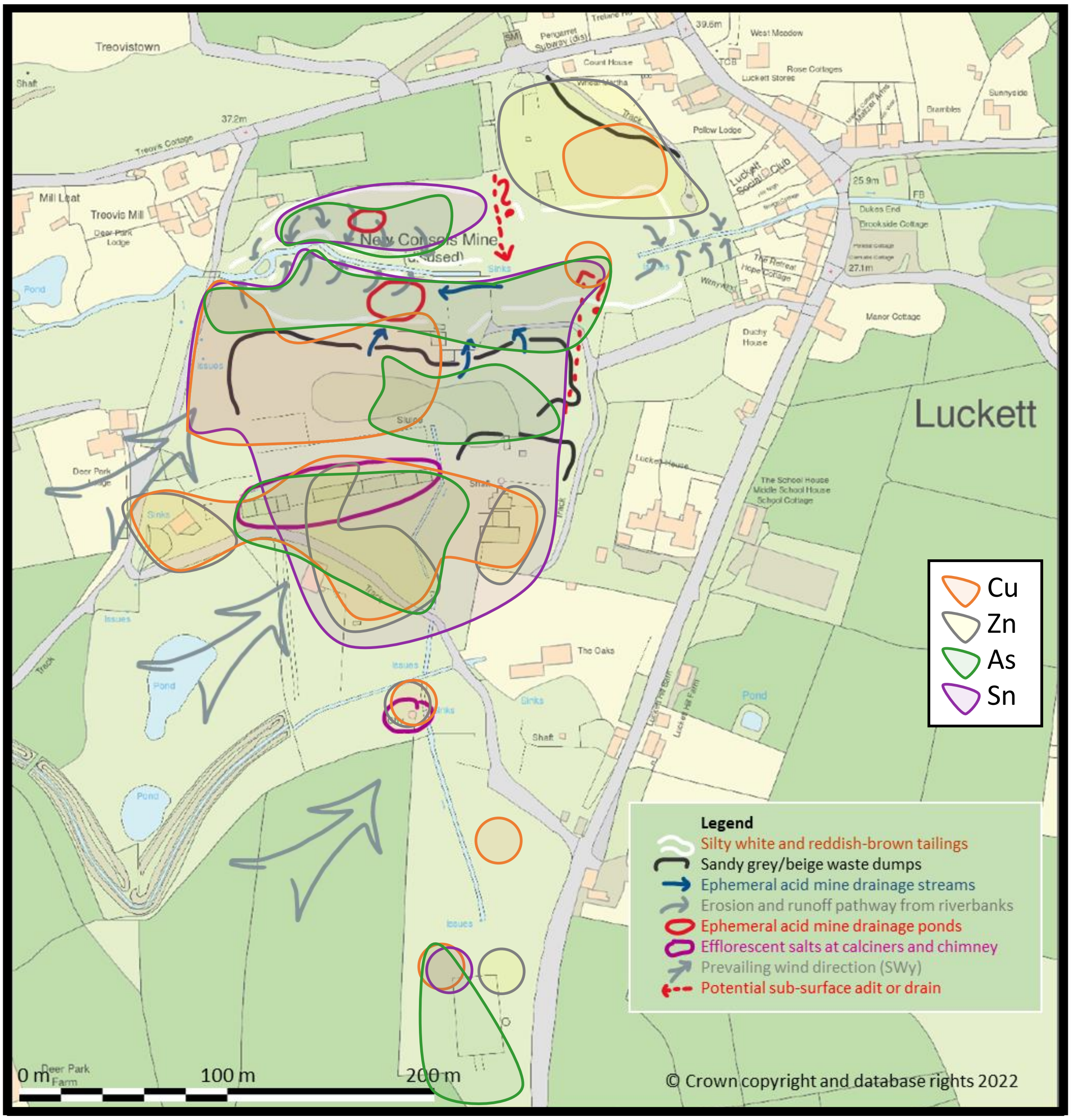

Figure 4-31 Combination of Figure 4-28 with Figure 4-30 with the purpose to identify metal/loid-specific sources and pathways at NGC. Please refer to the captions of Figure 4-28 and Figure 4-30 for more detail. Map base as for Figure 4-28 © Crown copyright and database rights 2023 Ordnance Survey 100049047.

Overall, the recent surveys revealed a complex picture of contamination sources, contamination pathways to the stream, as well as areas of attenuation and dilution within the Luckett Catchment. However, no detailed survey of surface hydrology is available, and subsurface hydrology remains unknown. The exceedance of environmental water quality standards for Zn and Cu at both, Old Mill and Luckett in contemporary surveys remains of concern. Attempts to improve the water quality in Luckett Stream will need to take into account inputs in the upper catchment, in particular from Holmbush mine (see Section 3.7.2), if not physically then at least with respect to managing expectations of the efficacy if remediation efforts are limited to the NGC site at Luckett.

In the context of evaluating sources of AMD in the upper catchment, it is worth noting that records indicate a hydrological connection between mines at Kelly Bray and Holmbush, and that deep mining for tungsten and tin may recommence at Kelly Bray (Redmoor Project by Cornwall Resources) within the coming years.

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5 Remedial Work at Abandoned Mine Sites

5.1 Aims and Scope

The aim of this section is to provide an overview of contaminated land remediation methodologies that are applicable to net-acid generating legacy metal/loid mines in general. In order to achieve this, scientific literature, case studies and reports are reviewed to present a range of solutions, their mechanisms, benefits, limitations and resource intensity. Particular focus is placed on approaches that work with nature and deliver benefits in terms environmental and economic sustainability.

5.2 Non-technical Summary

The drive to remediate legacy metalliferous mine sites in the Southwest derives its motivation from the regulative and legislative background of the Water Framework Directive, Mining Waste Directive and the Environment Act 2021, as well as the recent policy paper ‘Plan for Water’.

The findings of Sections 3 and 4 highlighted the complexity of contamination sources and pathways at New Great Consols and this is reflected in the wide range of potential remediation methodologies reviewed here. These include:

- physical removal and/or treatments of contaminated solids (e.g. excavation and disposal elsewhere, pump-and-treat washing and filtration, vitrification)
- chemical *in situ* and *ex situ* treatments (e.g. oxidation or reduction)
- biological techniques and nature based solutions (NBS) (e.g. microbial sorption or leaching, plant-based extraction of metals)
- nature based solutions (NBS) and green and sustainable remediation (GSR) (e.g. conservation measures, habitat restoration, erosion control using natural materials).

The project partners favour environmentally and economically sustainable solutions and therefore particular attention was paid to evaluate the purpose, function, benefits and limitations of NBS-GSR methodologies. As an example, erosion control using native, local plants has the advantage of reducing the wind-blown transport and run-off of contaminated particles, lessening infiltration of rain and hence leaching of contaminants and keeping footfall to a minimum. The establishment of vegetation on slopes of loose mine waste requires the addition of soil amendments that provide essential nutrients and organic matter to enhance soil moisture retention, as well as aggregate particles so that roots can gain a foothold. The main limitation of NBS-GBR approaches is their failure to completely stop pollution from leaving the site, as is also the case for some of the more invasive physical, chemical and engineering methodologies.

This section provides the theoretical information that underpins the considerations for site-specific interventions that reduce metal/loid export from legacy mine sites, which is presented for New Great Consols in Luckett in Section 6.

5.3 Regulative Background

The Mining Waste Directive (MWD, 2006) issued by the European Commission [48], requires EU Member States to provide inventories of closed mining waste facilities that are causing serious environmental impacts. The Environment Agency identified 150 sites that meet this criterion [49] in England and Wales, and within the UK the means by which action is taken to mitigate the risk include the Mines and Quarries (Tips) Act, Contaminated Land Regulations and the Water Framework Directive (WFD, 2003).

The provisions of the WFD drove efforts to assess the quality of river catchments in all EU member states and to develop management plans with the aim to improve the ecological status of water courses to at least 'good'. In England and Wales, the Environment Agency undertakes this work [50], which now entails the implementation of catchment management measures in collaboration with the Department for Environment, Food & Rural Affairs (DEFRA) [4]. Under the Contaminated Land Regulations (Part 2a, Environmental Protection Act 1990), local authorities have the duty to inspect sites where contamination is suspected to be causing adverse impacts on human health, water pollution, ecology or property, with the caveat that mine waters from mines abandoned before 1999 are excluded. This means that in most cases, no-one can be held liable for water pollution emanating from legacy mine sites in southwest England.

In January 2021, DEFRA published the UK government policy paper Plan for Water [51], which sets out a catchment-based approach to water management, and the allocation of resources to the restoration of catchments with the aims to provide flood risk management, carbon sequestration, clean water, drought resilience and amenity value. It refers to the legally binding target in the Environment Act 2021 (with updates) to '*halve the length of rivers polluted by harmful metals from abandoned mines by 2038*' [52] and the intention to use sustainable methods to achieve this.

In practice, the management of mine water pollution is led by the Coal Authority in partnership with the Environment Agency (EA). Any intervention aimed at improving water quality in the Luckett stream carried out for the Tamara Landscape Partnership programme will be made against the background of established environmental quality standards and targets. In this context, the copper contamination of Luckett Stream and the lower Tamar River are ongoing concerns and predominantly the result of the mining legacy in the region.

5.4 Principles of Metal/loid Remediation

5.4.1 Introduction

Contamination of soils, ground- and surface waters with metal/loids can be the consequence of natural processes. Well-documented examples are the deltas of several rivers, including the Ganges and Brahmaputra, where groundwater in alluvial aquifers is contaminated as a result of the geogenic weathering and erosion of mineral-rich geological formations in the Himalayan mountains and subsequent fluvial transport and deposition of arsenic-enriched sediments [53, 54].

However, environmental metal/loid pollution is more often the result of human activities, including the mining and processing of ores to obtain resources, the manufacturing of goods and their disposal. The geographic occurrence of resources and the location of production facilities and population centres has made metal/loid pollution a global concern, for which sustainable prevention and remediation are the subject of much research and development. Over 41,000 results for the search term "*sustainable metal remediation*" in a Google Scholar search for scientific papers published between 2019 and May 2023 illustrates this effort.

5.4.2 Legacy Metalliferous Mines in the UK

Historic mines sites in the UK present a particular challenge, as the treatment and disposal of potentially hazardous waste during the operation of mines were not regulated until the latter half of the 20th century. As explored at New Great Consols in Sections 3 and 4, without containment or remediation, the dumped mine waste and contaminated structures remain sources of potentially toxic elements for centuries. Metal/loid contamination may spread from its source into the wider environment from a point source, such as the outflow from an adit, but more often is of a diffuse nature. Figure 5-1 summarises the main diffuse sources and pathways of metal/loids at abandoned mine sites [55-57].

Even at legacy mines that have been abandoned for many decades, the metal/loid distribution in the environment is not static. Rather, elements are continuously moving between biota and environmental compartments, such as soil, groundwater, surface water, interstitial water, sediment, atmosphere. This biogeochemical cycling of elements is strongly influenced by continuously changing environmental conditions, including redox potential, pH, inorganic colloids, organic matter, grain size, moisture, cation exchange capacity, conductivity and flow dynamic, as well as the nature of the biota.

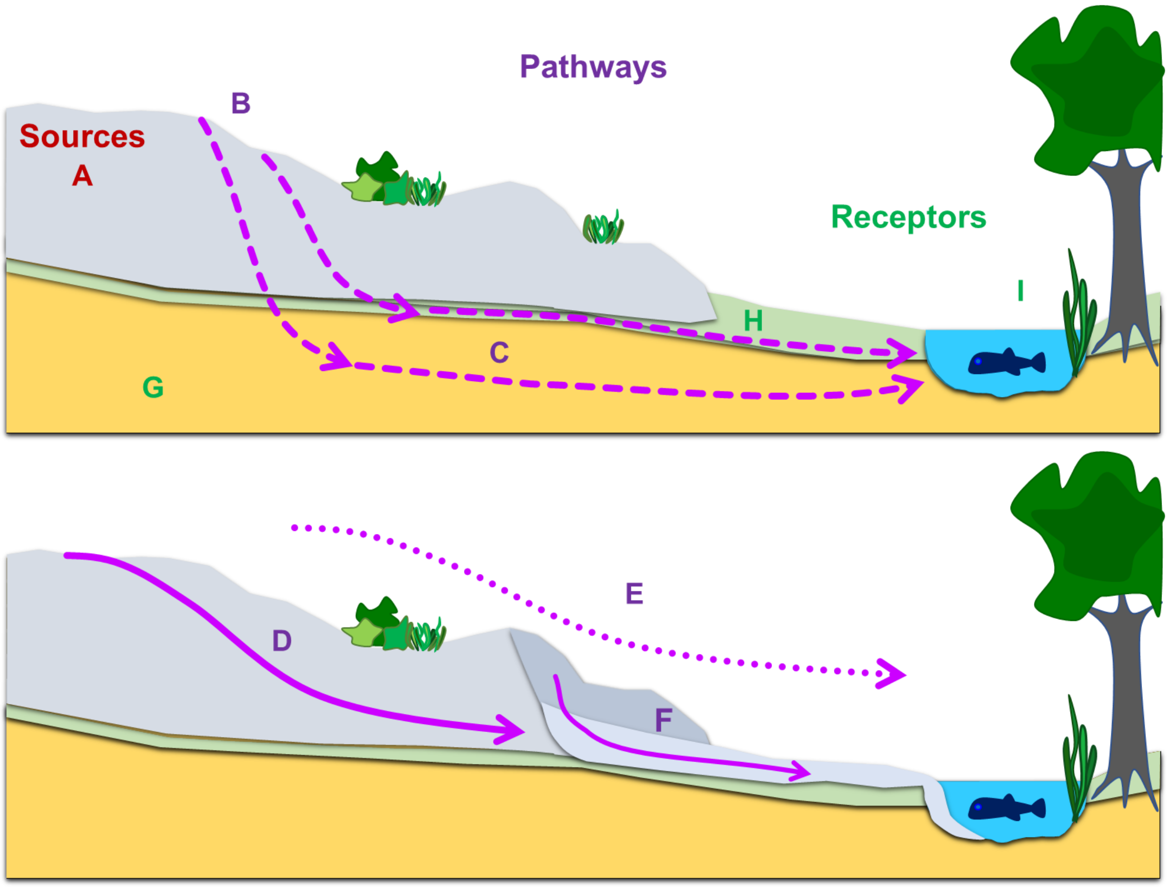

Figure 5-1 Conceptual model of the main diffuse sources (red), pathways (purple) and receptors (green) at abandoned mine sites, such as NGC in Luckett. The sources may include contaminated waste, structures and underground workings (A). Pathways include infiltration and leaching (B) followed by shallow or groundwater transport (C), physical erosion processes and gully formation followed by surface run-off (D) or saltation and aeolian transport (E); gravitational transport and slope failure (F) may spread contaminated material in the vicinity. The receptors are indicated symbolically and represent the bedrock and aquifers (G), soils and their microbiome (H), and surrounding ecosystems (I), including water courses, associated flora and fauna and potentially human habitation.

Remediation approaches also need to take into consideration the heterogeneous nature of legacy mine sites, with its diversity of buildings, shafts, crushers, calciners and mine waste of different characteristics. At many metalliferous mines in the Southwest that were operated in the 19th and early 20th centuries, ore processing utilised gravity to transport excavated materials downhill in a cascade of facilities that broke rock and crushed, ground, milled and separated ore from gangue. Consequently, increasingly finer materials were discarded, often leaving the finest wastes to fill river valleys. Advanced ore processing and re-processing of earlier waste deposits in the 20th century resulted in the creation of lagoons into which mine tailings were deposited in layers of slurry and left to naturally dewater and compact. At some mines, ore processing took place, adding wastes and buildings associated with calcination or roasting to these sites.

Specifically for New Great Consols (NGC) in Luckett, the sources of contamination identified in Sections 3 and 4 include contaminated mine waste, buildings, structures and soils on associated land. The main pathways of contamination from NGC into Luckett stream and surrounding areas are (Figure 4-30):

- infiltration of precipitation and consequent leaching of contaminants and their transport into and within soils or groundwater,
- infiltration of surface and groundwaters into mine waste and underground workings, mobilisation of contaminants and subsequent transport with groundwater flow and/or adits into the river,
- physical erosion via freeze-thaw, rain pitting, saltation, wind-blown dust, footfall, surface run-off and gully formation, and gravitational slump and slope failure.

As a result of these processes, receptors are exposed to metal/loids in dissolved and/or solid phases in water courses or on land. Much of the NGC site has naturally revegetated with communities ranging from early succession (lichens, bryophytes, grasses) and shrubland with elements of lowland heath (grasses, herbs, heather, gorse, bramble) to woodland (bramble, ferns, hazel, birch, spindle, sycamore, beech, oak). This vegetation cover alleviates some of the physical pathways of metal/loids into the wider environment. Vegetation also constitutes receptors that take up metal/loids via roots and contact with the leaf epidermis, while also attracting other receptors (invertebrates, mammals, birds) onto the site.

5.4.3 Remediation Technologies for Legacy Metalliferous Mine Sites

The remediation of sites contaminated with metal/loids can be achieved with a wide range of physical, chemical and biological processes and technologies that may be applied in isolation or in combination. These focus on the removal or isolation of contaminants or the conversion of contaminants into chemical species or physical forms that are characterised by low(er) mobility, biological availability and/or toxicity [58]. Key interventions at legacy mines are suitably based on the source-pathway-receptor principles and include:

- reduction of contamination **sources** through the removal of contamination or contaminated materials from the site, for example excavation, phytoextraction or chemical extraction,
- interruption of **pathways**, for example by covering contaminated materials to prevent erosion and/or infiltration or through the interception of leachate or airborne material with suitable membranes, barriers, lagoons or screens,
- protection of **receptors**, largely indirectly, for example by removing receptors or the interruption of contamination pathways to receptors.

Figure 5-2 illustrates some of the principal methods of remediation in the context of source removal and pathway interruption with reference to Figure 5-1.

Important remediation approaches are summarised in Table 5-1 with a brief outline of required inputs and resources. A key advantage of physical and chemical treatment options is their efficacy in source removal or pathway interruption. However, many have severe drawbacks, that include high cost, land footprint, energy consumption and carbon footprint, as well as low public acceptance [59]. In addition, some use and release synthetic reactants into the environment, mobilise non-target metal/loids or make them more biologically available, produce secondary pollution on site or elsewhere, may require treatment and disposal of hazardous waste, change the site appearance and alter soil structure and function. Their application may be best placed for relatively small, high value and highly contaminated areas where rapid and effective hazard removal is required to remediate the site for a specific land use [60].

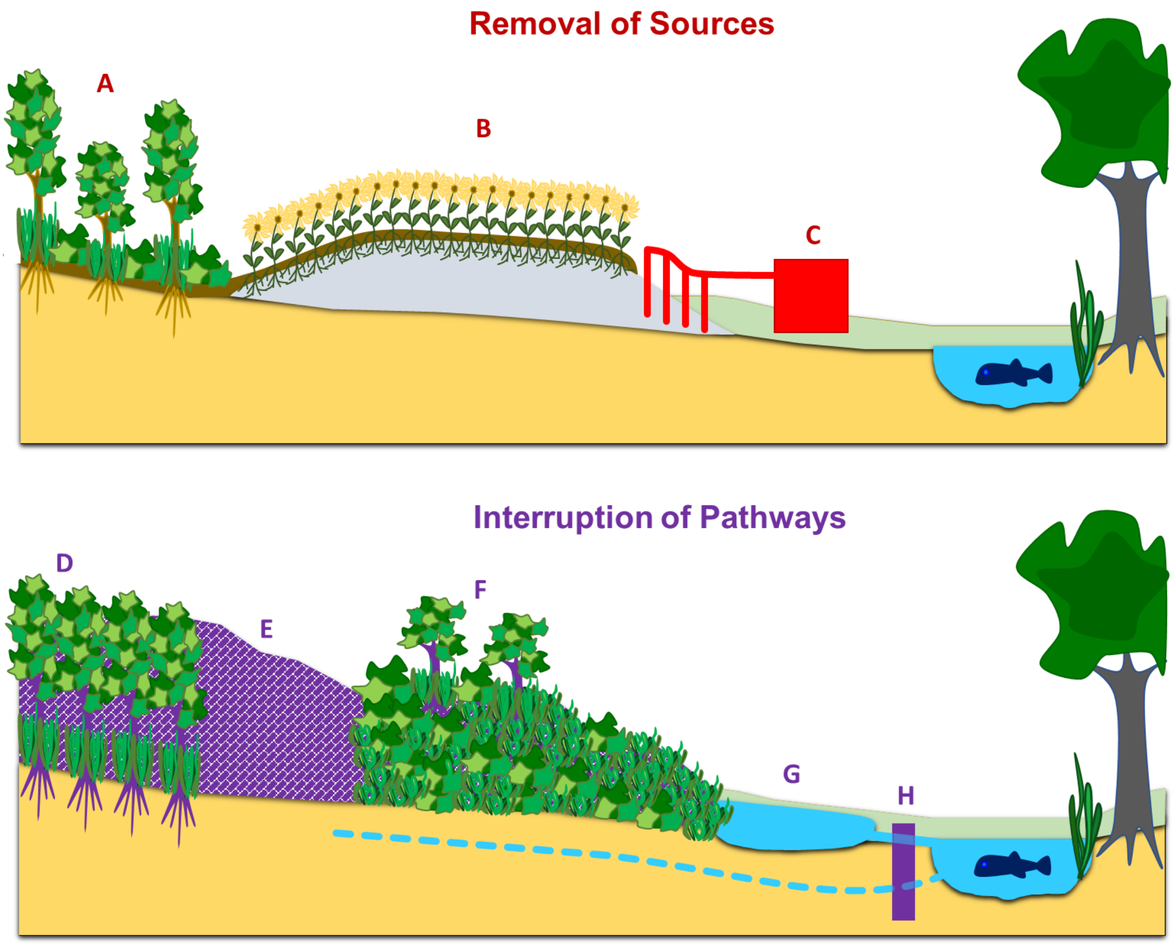

Figure 5-2 Illustration of some interventions that address sources, pathways and, indirectly, protect receptors. Original state of mine site as in Figure 5-1. A) Removal of contaminated material by excavation and disposal of hazardous waste elsewhere, followed by import of topsoil and re-establishment of habitat that provides ecosystem services; B) grading of legacy mine waste to prepare terrain for agricultural work, import of topsoil and/or soil amendments that support growth, followed by plantation of hyperaccumulator vegetation that will be harvested to remove and/or phyto-mine contaminants; C) extraction of contaminants through in situ *chemical extraction or excavation, washing and replacement of treated material on site; D) interruption of aeolian pathway by plantation of vegetation screen and hydrological control by reducing groundwater movement around the site through evapotranspiration; E) isolation of contaminated material using geomembranes and/or clay cover to prevent erosion and infiltration and leaching of contaminants; F) addition of soil amendments and erosion control to allow permanent revegetation (natural or introduced) and provide amenity, erosion control and reduction of infiltration and leaching; G) establishment of settling pond or lagoon to trap particles and potential phytoextraction of contaminants; H) emplacement of semi-permeable barriers to treat contaminants in pore- and groundwater.*

Table 5-1 Summary of important physical, chemical and biological methods for the remediation of land contaminated by metal/loids[58, 60] [61] [62] [59, 63].

Approach	Principle	Method	Inputs/Resources/Requirements
Physical Removal	Excavation	removal of contaminated material & landscaping	excavation plant, disposal of contaminated waste
	Extraction	leaching or washing either pump-and-treat *in situ* or *ex situ* using extractants and/or adsorbants or filters	bore holes and pumping facilities, water with or without extractants (e.g. acids, bases, salts, chelators, surfactants), treatment and/or disposal of waste
	Electrodeposition	pump-and-treat system with *ex situ* or *in situ* extraction of metals	bore holes and pumping facilities, water, electrodeposition plant, disopsal or metal recovery
	Thermal Desorption	separation by volatalisation	excavation for on-site or ex situ treatment in kiln, suitable for volatile elements, such as Hg
	Physical Separation	removal of contaminated material by physical properties (size, density, etc.)	excavation and sorting plant, disposal of contaminated waste, followed by landscaping
Physical Treatment	Vitrification	immobilisation of contaminants using electric currents	installation of thermal treatment infrastructure on site
	Stabilisation	immobilisation of contaminants using soil amendments	top-dressing or physical mixing with metal binding materials, e.g. biochar, organic waste, zero-valent iron
	Extravagation	isolation of mine waste with uncontaminated soils and/or clay	machinary, top soil and/or clay, landscaping
Chemical Treatment	Oxidation or Reduction	rendering contaminants less toxic and/or less mobile	top-dressing or physical mixing with oxidising (e.g. metal oxides, potassium permanganate, hyrogen peroxide, chlorine dioxide) or reducing agents (e.g. hydrogen sulfide, sodium bisulfite, zero-valent iron)
	Immobilisation	addition of amendments & physical mixing	top-dressing or physical mixing with e.g. lime, phosphate, calcium carbonate, fly ash, cement, slag, bauxite residue, clay

(Table 5-1 continued on next page)

(Table 5-1 continued)

Approach	Principle	Method	Inputs/Resources/Requirements
Biological Techniques (GSR-NBS)	Bioremediation	degradation or modification of contaminants to change mobility, biological availability or toxicity through degradation, oxidation, reduction etc.	addition of microorganisms or induction of microbial processes using supporting materials, repeated inoculation may be necessary
	Biosorption	immobilisation of contaminants on cell surfaces, intra- and extracellular parts of microorganisms and/or soprtion to their metabolites	addition of algae, bacteria, yeasts and/or polysaccharides, extracellular polymeric substances etc., repeated inoculation may be necessary
	Bioleaching	utilisation of specific microorganisms to mobilise contaminants and recover resources	excavation and treatment of contaminated material with leachate collection facility, treatment of leachate
	Phytoaccumulation	extraction of contaminants at relatively low concentration using plants that selectively bioaccumulate metal/loids in their standing biomass	landscaping and soil amendments, followed by planting, cultivating and harvesting of plants over many years, additives to increase mobility and biological availability of contaminants
	Biological Phytostabilisation	stabilisation of contaminants within plant roots or precipitation in rhizosphere as a result of root exudates	soil amendments that improve soil and may include metal/loid mobilising chemicals, establishing metal/loid tolerant species of perennial plants
	Physical Phytostabilisation	physical stabilisation of contaminated land against erosion using plants that cover and bind contaminated matrix	soil amendments to encourage natural colonisation by native vegetation or planting metal/loid tolerant species with suitable properties
Green & Sustainable Remediation	Protection (GSR-NBS)	conservation and prevention of deterioration of existing ecosystem services	access to land, application of close-to-nature approaches (e.g. establishment of vegetation cover, encourage natural revegetation of degraded land, erosion prevention, leaky dams, enhance diversity) to protect, restore and/or manage ecosystems
	Restoration (GSR-NBS)	active or passive restoration of habitat, structure, ecology etc.	
	Creation (GSR-NBS)	estabilshment of ecosystems on degraded land	access to land, potential soil enhancement, returning and maintaining natural vegetation
	GSR Modification of Techniques	sustainable modification of physical, chemical or biological techniques	research & development to introduce natural reagents and processes into established techniques, e.g. biodegradable reactants for soil washing

The desire to find more economically, socially and environmentally sustainable solutions has led to a greater focus on nature-based solutions (NBS) [63]. Hereby, it is recognised that pristine or fully natural conditions cannot be restored and hence, there is no requirement for the removal of contaminants in their entirety [59]. Rather, NBS aim to remediate sites for specific purposes and therefore, it may be sufficient to reduce toxic effects or partially interrupt pathways from sources to receptors and enhance the amenity of a site. Green and sustainable remediation (GSR) strategies take into account social and economic sustainability and consider impacts beyond the site boundary and on future generations. Hence, GSR techniques include biological techniques, as well as sustainably modified physical and chemical processes [58, 59].

NBS/GSR techniques are typically low- to medium cost, focus on working with nature and often enhance ecology, flood protection, air and water quality, amenity and site appearance and provide climate change mitigation [63][59]. However, some share certain disadvantages with physical and chemical approaches, for example potentially enhancing the leaching of non-target contaminants [64]. They often take a long time to establish and take effect and they have limited potential for contaminant removal. Furthermore, the NBS/GSR intervention design for degraded and contaminated land may require cultivation, application of soil amendments and maintenance over long periods, some introduce non-native species, while natural materials used in erosion control and flood prevention may need periodic replacement as they deteriorate.

One of the greatest challenges for NBS/GSR approaches that utilise microorganisms (MO) or flora is the nature of metalliferous mine waste, which is not conducive to plant growth and prevents many MOs from thriving because:

- the substrate structure either lacks cohesion and moisture retention or is compacted, poorly ventilated and of low permeability,
- toxic effects from contamination with an array of metal/loids include disruption of morphological and physiological processes in plants (growth rate, stomatal movement, photosynthetic processes, nutrient imbalance, oxidative damage [65]),
- in net acid-generating wastes, the pH may be very low (<4.5), so that moisture infiltration or groundwater flow becomes acidified and enriched in toxic elements (AMD – acid mine drainage generation),
- low cation exchange capacity and low (micro)nutrient retention
- high salinity,
- extreme pH conditions, either very low in sulfidic metal/loid mining waste (pH<4) or high in the case of red mud (pH > 12)
- lack of nutrients (N, P K) and organic matter.

As a result, mine wastes are not functioning soils and the combination of their characteristics adversely affects the biomass, diversity and structure of soil microbial communities, invertebrates and the colonisation with and growth of flora [60]. Yet revegetation has become a key step in the restoration of many industrial sites, closed landfills, mines and other derelict land, as it controls erosion and promotes soil formation, nutrient cycling, the establishment of healthy soil microbiomes, as well as improving the aesthetics and being cost effective [66].

Natural succession may occur gradually over decades, as organic matter accrues on site through atmospheric deposition of leaf litter, algae and lichen spores from surrounding areas, as well as the faeces of passing animals. However, vegetation establishment is physically hampered by erosion and drought on waste slopes and water logging in tailings and therefore, natural revegetation on abandoned mine sites may remain incomplete for centuries.

Biological and nature-based remediation techniques seek to accelerate the natural revegetation process by reducing erosion and controlling water flow, as well as enhancing the physical and chemical characteristics of the substrate through soil amendments and reducing toxicity (Table 5-1). Hence, in addition to using natural materials in erosion and flood control, the development of sustainable soil amendments plays a key role in GSR/NBS, with recent research focusing particularly on waste-derived materials (e.g. biochar, compost, red mud), natural minerals (e.g. montmorillonite, zeolite, diatomite) and sustainably synthesised nanomaterials (e.g. nano zero-valent iron) [59].

5.5 NBS/GSR Strategies for Abandoned Metal/loid Mines in the Southwest

5.5.1 Sustainable Site Management

Plant-based remediation strategies are at the core of sustainable site management. These include the phytomanagement of site perimeters, phytostabilisation of the derelict land itself and phytoextraction or phytomining on derelict land or on the surrounding environment. All organisms require metal/loids as micronutrients that fulfil important roles as, for example, cofactors of enzymes, in hydrolysis, photosynthesis, energy transfer and more. Therefore, plants have the capability to take up essential metal/loids from the soil and porewater and move or store them within their tissue as required. Metallophytes are plants that are particularly able to resist, tolerate or thrive on soils with a heavy burden of metal/loids, and therefore are used for plant-based remediation approaches [67].

Furthermore, plantations impact on the hydrology of a site because they change the partitioning of:

(a) precipitation inputs between the vapour and liquid phases through transpiration and canopy interception and
(b) of liquid fluxes between run-off and fast flow versus deep drainage and base flow by reducing infiltration and re-routing surface water flow.

Sustainability arises from potential social, economic and ecological benefits of the chosen site management options [68] [69]. With the exception of phytoextraction, phytoremediation approaches do not remove contaminants from the site, and while this can be seen as a major disadvantage, it is a recognition of the reality on the ground: legacy mine waste dumps and tailings are voluminous and any large-scale disturbance, such as reworking for resources, excavation and removal to a managed disposal site is often impractical.

5.5.1.1 Phytomanagement of Site Perimeters

Mine site remediation may benefit from the sustainable management of the land surrounding the contaminated area itself. In this context, the ‘site perimeter’ is defined as outside of the mine site with its spoil dumps, tailings and structures and is characterised by soil with a low contamination burden. Although potentially limited by the need to acquire ‘perimeter’ land or obtain stakeholder co-operation, the phytomanagement of mine site perimeters can provide a range of wider benefits:

i) Specific assemblages of native species may be encouraged to thrive or planted specifically to restore and enrich the local habitat and enhance the diversity of flora and fauna in the region. In this context, mine and/or perimeter restoration provides an opportunity to counteract the loss and fragmentation of key habitats within the region and contribute to nature conservation [70]. An example in southwest England are efforts to restore Atlantic heathland on China clay quarries, which highlights the challenges associated with optimising soil characteristics to successfully restore specific communities [71]. More generally, enhancing the connectivity of hedgerows and woodlands can benefit important pollinators [72], birds and mammals and this may be of interest to stakeholders in the local community of farmers and landowners.
ii) Species planted in formations that reach sufficient height and density throughout the seasons around (and potentially on) mine sites increases the roughness of the ground cover, which decelerates wind velocity at ground level and hence diminishes saltation and aeolian erosion of contaminated materials. However, it is important to consider design criteria that minimise turbulence in the luv and lee

of high canopies and avoid abrupt changes of height in the vicinity of bare mine spoil or tailings [73].

iii) Plantation of fast growing species with high water demand, such as poplar and willow, on perimeter land can contribute to the hydrological control of sub-surface flow with respect to reducing ground water movement through evapotranspiration [74, 75]. Tree-facilitated hydrological control can be deployed 'upstream' of the site to lower the water table and reduce groundwater ingress into contaminated materials, such as spoil on mine sites, thus reducing leaching potential. Alternatively or in addition, tree plantations may be used 'downstream' to intercept and reduce any plume of contaminated shallow groundwater emanating from the site and protect water courses. A range of poplar and willow species have been shown to being tolerant to metal contamination, with some being hyperaccumulators [75]. It should be noted that in temperate regions, plant-based hydrological control measures are only effective during the growing season.

iv) Phytoextraction of contaminants from perimeter land may be indicated where metal/loids have spread from the mine site over time and affect the surface soils of surrounding land (see Section 5.4.3).

v) Phytomanagement of site perimeters contribute to (seasonal) carbon sequestration and hence play a role in climate change mitigation [63]. In addition, it may offer an opportunity for revenue through coppicing for biomass production or charcoal, and by growing material that can be used to construct living fences and erosion control measures, such as willow hurdles, spiling or mats [76].

vi) Planting schemes along site perimeters provides a screening effect that affords visual enhancement of the landscape, which may benefit the local population and tourism and recover land or property value [68]. On the other hand, screening potentially hides important industrial archaeology and heritage from view.

5.5.1.2 Phytostabilisation

Largely employed on the contaminated areas of derelict mine sites, such as tailings and mine spoil dumps, phytostabilisation aims to prevent or lessen the toxicity of metal/loids and their off-site transport. In order to achieve this, specific plants that exhibit tolerance to metal/loid contamination (metallophytes) are introduced in combination with soil amendments and, at times, bacteria (see Section 5.5.2). Typically, the root zone on phytostabilised mine sites does not reach the entire depth of the contaminated material. Rather, the direct stabilising effect pertains to near the surface, therefore also protecting deeper layers of waste material from erosion and leaching. Phytostabilisation makes use of ‘excluding’ detoxification strategies of plants in response to metal/loid exposure, including [59, 61]:

- some metallophytes use transport chemicals that facilitate the take-up and other chemicals that enable ‘safe’ storage of metal/loids within the root system, preventing the translocation into shoots and leading to the retention and immobilisation of metal/loids below ground,
- some metallophytes release root exudates to reduce metal/loid toxicity by changing the redox potential or pH of the rhizosphere and hence change the speciation of metal/loids,
- some metallophytes release root exudates to reduce the mobility and biological availability of metal/loids, and hence reduce uptake, for example by chemical precipitation, enhanced adsorption to root surfaces or strong chelation by organic molecules too large for roots to take up.

It should be noted that the biological availability, mobility and toxicity of different metal/loids differ for any one pH/redox condition, so that changes in the rhizosphere produced by plants may be effective in remediating a specific element or group of elements but may mobilise another. For example, arsenic oxyanions become more mobile with increasing pH values, while the solubility of many of the ‘heavy’ metals decreases.

In addition to the characteristics of the plant-metal/loid interaction listed above, phytostabilisation also physically stabilises the substrate and reduces export [74, 77]:

- plant roots physically bind the substrate, diminishing physical erosion,
- plant cover intercepts rainfall and reduces the erosion potential of heavy precipitation (surface run-off and gully erosion) and provides insulation to lessen freeze-thaw weathering,
- plant cover increases surface roughness and reduces wind velocity at ground level (see Section 5.5.1.1), traps airborne particles and reduces saltation and aeolian transport of contaminated materials,
- evapotranspiration moderates water infiltration and reduces (but not completely ceases) the potential for leaching of contaminants into groundwater and surface water courses,
- litter from flora as a result annual cycles provides a source of organic matter, which encourages the development of soil by supporting MOs and invertebrates, over time leading to a self-sustaining ecosystem and natural succession on site (also see 4.3).

In practice, the selection of plants for phytostabilisation may be based on two distinct approaches, employed either alone or in combination [66]:

i) encouragement of self-sustaining plant communities native to the location with suitable soil amendments and erosion control for slopes and loose materials,
ii) establishment of non-native or non-local plant species featuring desirable characteristics with the aim to expedite the revegetation process.

The vegetation in the vicinity of a long abandoned mine site may over time encroach on its margins through soil development afforded by leaf litter ingress from surrounding land. Although this natural addition of organic matter somewhat dilutes the contamination and provides nutrients, plants colonising a site naturally are likely to be metallophytes and often indicate assemblages that could be successfully established across as yet barren contaminated areas. Many species native to the Southwest exhibit phytostabilisation characteristics. To overcome the inhibitors to revegetation of mine waste, it is prudent to survey the plants that naturally colonise abandoned mine sites. Examples, with important plant characteristics underlined, are:

- Calcifuge plants are those that prefer acidic soils and include the *Ericaceae* (heather family), many *Betula* (birch) species, *Ulex* (gorse), *Digitalis* (foxglove) and some *Pinus* (pine) species.
- *Erica* and *Calluna* spp. are calcifuge members of the *Ericaceae* family and often establish spontaneously on mine tailings, as they tolerate low-quality, acid, water-logged soils, utilising mycorrhizal fungi to assist with extracting nutrients from infertile soils. They are evergreen, which conserves nutrient consumption and affords year-round vegetative cover. Some *Erica* species exhibit high tolerance to metal contamination [78] [77].
- European or common gorse (*Ulex europaeus*) is a calcifuge and successful on coarse-grained mine spoil because of its preference for open, sunny locations, resistance to drought afforded by green stems with very small leaves, and resistance to grazing because of its thorniness. As part of the pea (Fabaceae) family, it has nitrogen-fixing capacity, so it does not rely on taking up nitrogen from the soil. *U. europaeus* is a metallophyte, even at low pH values, that does not translocate metal/loids into shoots [77].
- Combinations of nitrogen-fixing plants (green manure) with grasses (grass-legume mixture) may be particularly useful for the rapid colonisation of slopes, as it overcomes poor nutrition and binds substrate with strong root systems [79].

- Downy or moor birch (*Betula pubescens*) colonises mine tailings because of its shallow roots are adapted to wet, heavy soils of poor drainage. It is a pioneer species distributed by tiny seeds on the wind to reach cleared land and is acid tolerant.
- Willow species, (*Salix*) are among typical fast-growing pioneer vegetation on mine sites. They have high metal tolerance as a result of ectomycorrhizal fungi that support the plant against abiotic stress [80] [81]. Salicylic acid, first isolated from willow tree bark, plays an important role in plant defence against stress factors, ranging from insect attack to high metal concentrations.
- Creeping colonisers, including ivy and bramble may range far from the parent plant, which may be rooted in soil of adequate quality and low contamination.
- Some ferns and wild flowers exhibit calcifuge and/or metallophyte characteristics (e.g. diverse ferns and bracken, digitalis, bladder campion etc.) [61].
- A range of metallophyte native grasses colonise abandoned mine sites and many of them are considered metal excluder species, although some are hyperaccumulators and have been used in phytoextraction. *Agrostis capillaris* (common bent) is often seen as pioneer on mine waste dumps following the establishment of lichens and bryophytes and its root mats contribute to stabilising loose materials and slopes. Native grasses used for phytostabilisation include *A. capillaris* (Cu, Pb) and *Festuca arundinacea* and *F. rubra* (Cd, Cu, Pb, Zn) [61, 82].

In summary, calcifuge metallophytes adapted to infertile soils and with further adaptations to specific substrate conditions (lose, coarse grained, well-drained or waterlogged, compacted materials) are desirable options for revegetation of mine sites. Hereby, leguminous annuals that add nutrients and organic matter could be used in combination with fast-growing and/or evergreen perennials that provide erosion control.

Depending on specific site characteristics and desired outcomes, non-native species may be considered in phytostabilisation. The available options range too widely to do justice here, from fast-growing grasses (e.g. *Miscanthus spp*.) with biomass capacity to ornamental Mediterranean herbs, such as *Lavendula pendunculata*, which has been identified as tolerant of soils with multi-elemental contamination, low fertility as well as withstanding drought conditions [83] [84].

5.5.1.3 Phytoextraction/Phytomining

Phytoextraction and phytomining utilises a natural strategy for detoxification and/or predation deterrence that some metallophytes exhibit. These plants actively take up metal/loids through their roots and translocate them to shoots at a high rate, then store them 'safely' in their tissue. Hypertolerant hyperaccumulators feature genetic traits that are found in over 500 plant species in a wide variety of families, including *Brassicaceae* (diverse species: As, Cd, Co, Au, Pb, Mn, Ni, Se, Ag, Tl, U, Zn), *Asteraceae* (e.g. Jerusalem artichoke, sunflower: Ni, Cr, Cu, Mn, Zn, Cd, As), *Lamiaceae* (e.g. lavender: Pb, Cd, Zn), grasses (e.g. *Agrostis, Miscanthus, Vallisneria, Festuca, Triticum*), willow (*Salix*), poplar (*Poplus alba*) and ferns (*Pteris*). Hyperaccumulators are often specialist to one or a few metal/loids, which they accumulate in 100 to more than 1000 times the concentration found in tissues of similar species or populations [67] [65, 85]. Desirable characteristics of plants used for phytoextraction and phytomining include [67]:

- high biomass, fast growing,
- high tolerance to a range of metal/loids,
- high translocation factor from roots into shoots,
- adaptability to site-specific conditions related to soil characteristics and climate,
- ease of cultivation.

Typically, high biomass producing plants take up metals at lower concentrations than low biomass plant species, so that in many cases, a trade-off between desirable characteristics may be required, and genetic techniques, such as genome editing are being trialled to overcome those limitations [86]. High biomass production is also desirable for further use of harvested plants, for example in biodiesel production or power generation [65].

Phytoextraction and phytomining approaches are limited physically by the need to access land regularly for cultivation and harvest and the depth of efficacy within the root zone. Therefore, the extraction of metal/loids for either disposal or recovery is limited to relatively flat or suitably contoured land that can be cultivated using agricultural techniques and machinery.

Phytotechnologies are also chemically limited to the tolerance levels of plants to multi-elemental contamination and other factors, such as soil pH, redox potential, moisture and organic matter content, all of which influence the biological availability of metal/loids to plants. For example, many hyperaccumulator plants release organic acids (e.g. malic, oxalic) into the soil to decrease the pH in the rhizosphere and enhance the biological availability of metals. Plants and diverse MOs release siderophores into the rhizosphere to bind the metals and facilitate their transport across cell membranes and into roots.

Hence, the combination of bacteria and mycorrhizal fungi with phytoremediation techniques is a growing field of research attention [67].

With phytoextraction, it may take decades, hundreds or even thousands of years to lower the concentration of potentially toxic elements to levels that meet regulatory requirements and harvested plants have to be treated as contaminated biomass. Costs are highly site-specific (tens to thousands of pounds per cubic metre) and phytomining is highly sensitive to commodity prices, and hence most suitable for precious metals [59]. During the cultivation season, some of the benefits of plant cover highlighted for phytostabilisation apply (Section 5.5.1.2), but there may be a need for substrate disturbance through tilling, which may increase compaction, leaching and erosion during non-vegetative periods. Land that is impacted by mild to moderate contamination in surface soils, perhaps from nearby mines, ore processing facilities or other industries can be an application that takes advantage of the benefits of phytoextraction without suffering many of its limitations, especially when combined with biomass production for sustainable energy generation.

5.5.1.4 Soil Amendments for Phytostabilisation and Phytoextraction

Plant-based remediation techniques require adequate nutrition, soil physico-chemical characteristics, soil moisture and structure. As highlighted in Section 5.4.3, mine spoil heaps and tailings present multiple site-specific challenges that need to be addressed in the design stage for phytoremediation.

A wide range of soil amendments have been developed and applied to mine wastes in order to create technosols suitable for revegetation. Such amendments range from traditional agricultural additives (e.g. inorganic fertilisers, manure) and industrial waste materials (e.g. red mud, coal fly ash) to top soil, sustainably sourced wastes (e.g. biochar), minerals (e.g. iron oxides, clay) and nanomaterials (e.g. zero-valent iron, silver) [55, 59].

The conditioning of soil is achieved with topical application of amendments in form of solids or fluids and may require agricultural techniques, such as tilling or mixing to work materials into the surface soils. The latter should be considered carefully on mine wastes, as it can lead to enhanced mobilisation of contaminants through physical erosion or leaching. In the case of sulfidic mine tailings, tilling will freshly expose particle surfaces to oxidising conditions and water, which leads to relatively rapid oxidation and dissolution of metals. In contrast, in mine spoil heaps that have been physically stable for a long time, secondary minerals form on surfaces of some primary minerals, and these have a shielding (pacifying) effect [30]. As a result, the reactions that lead to the release of potentially toxic elements progress more slowly and conditions are geochemically more stable with respect to rapid changes in pH, oxygen availability and reactivity of minerals, and hence are more tolerable by plants [55].

A review of phytoremediation field trials [55] showed that in many cases the remediation benefits of soil amendments on mine tailings are relatively short-lived and do not sustainably condition the growth medium in the long term. The authors related the failures of newly established plant communities within a few years to the continued poor soil structure and function in the root zone. Self-sustaining revegetation relies on the stimulation of soil formation in technosols and until this is achieved, a continuous input of remediating resources, such as organic matter and nutrients may be required for plants to survive.

Some of the more successful soil amendments are summarised below [55, 59, 65, 68, 71, 87-90], whereby additives that are likely to add high amounts of contaminants (i.e. red mud, coal fly ash, metal oxides, nano materials etc.) are not considered:

Topsoil: The addition of a topsoil layer across mine spoil or tailings can be a good starting point for phytoremediation of mine sites where the rapid prevention of erosion and establishment of habitat is required. Topsoil provides a non-compacted layer rich in organic matter, nutrients, that is of suitable pH and cation exchange capacity. It should be noted that the long-term storage of topsoil in heaps or windrows changes the soil structure, microorganism and invertebrate communities, nutrient and cation status and may not be an adequate growth medium by itself [71].

Frank Mills Mine in the Teign Valley presents an interesting example: part of a mine spoil heap was covered with topsoil (ca 0.5 m) some 100 years ago to enhance its visual impact. Today, a modest woodland habitat of native herbs, shrubs and somewhat stunted trees covers the site, even though bioturbation and capillary rise has brought elevated metal concentrations into the surface soil (unpublished data). The success of this measure may be in part due to the high natural precipitation in the region, therefore not requiring irrigation.

Plants generally require a stable and hydraulically functional soil horizon beneath the root zone. Therefore, tilling of waste before topsoil applications can improve the hydraulic connectivity between topsoil and compacted fine-grained mine tailings and prevent (or relocate to deeper in the substrate) an impermeable pan-effect and water logging. This may also be indicated in the case of coarser grained mine spoil heaps in which chemical cementation or iron pan formation obstructs permeability.

Over time, plant roots will reach the interface of topsoil with the mine spoil or tailings beneath and encounter a sharp increase in adverse characteristics, such as acidity and toxicity. Mixing of mine wastes with topsoil using agricultural techniques may present a more challenging substrate for plant establishment initially, but can be beneficial in the longer term by providing more of a continuum that can be particularly successful in combination with metallophyte plants.

Hydro-geochemical stabilisers: understanding of basic mine spoil geochemistry is key to the success of phytoremediation efforts. In the case of net-acid generating sulfidic mine wastes, the rapid oxidation processes of surfaces freshly exposed as a result of remediation measures may release a spate of metal/loids into pore and ground waters and present acute toxicity of metals and pH to newly established plant communities. The employment of hydro-geochemical stabilisers may help to mitigate these risks but may also exacerbate them. In some cases, it may be desirable to employ a strategy of exhausting the oxidation capacity of sulfidic mine spoil to prepare a less toxic technosol for phytoremediation and accept the short-term release of potentially toxic elements into ground and surface waters for long-term benefits. Equally, for phytoextraction and phytomining, the mobilisation of metal/loids to enhance biological availability is desirable while also posing and increased risk of groundwater contamination, in particular during dormant seasons.

For example, the incorporation of slow-rotting organic matter (e.g. wood chips or hay) enhances the permeability and porosity of technosols and stimulates the oxidation of sulfide minerals by allowing infiltration of water and diffusion of oxygen into deeper layers, thus releasing contaminants into porewaters. Well-composted animal manure or biosolids applied to mine spoil enhance the characteristics of technosols, as well as increasing the mobility of elements that are strongly complexed by humic substances, such as copper and nickel.

Although metal oxides are not covered in this report because they potentially introduce toxic metals to technosols, iron oxides (e.g. α-Fe_2O_3) and iron oxyhydroxides (e.g. α-$FeOOH$, γ-$FeOOH$) are an exception as amendment for mine waste that contains very low iron concentrations. Iron is an important micro-nutrient for plants and iron oxides and hydroxides stabilise both, metals and metalloids by inner-sphere complexation.

The raising of soil pH through liming using natural minerals (e.g. zeolite, moler, diatomite, clay minerals, calcium carbonate, dolomite) lowers the mobility and biological availability of many metals (e.g. Cu, Fe, Mn, Pb, Cd) and promotes precipitation of secondary minerals. Some natural minerals have stabilising effects on metals beyond the raising of pH. For example, the microporous structure of the alkaline aluminosilicate mineral zeolite immobilises metals via non-specific adsorption. The siliceous mineral diatomite has capacity for surface complexation and non-specific adsorption of metals. Clay minerals in combination with humic substances enhance the ion exchange capacity and stabilise metals via surface complexation with an abundance of hydroxyl functional groups. The precipitation of secondary minerals can also be achieved through addition of phosphate-based materials.

On remediation sites with high arsenic contamination the higher mobility of metalloids at alkaline pH values needs to be taken into account when using hydro-geochemical stabilisers that raise the substrate pH, i.e. have a liming effect.

Organic matter: in general, the addition of organic matter (OM) to mine waste improves many properties of technosols by buffering soil pH, promoting water infiltration and enhancing the water-holding capacity and nutrient status. In addition, OM stimulates the development of a healthy microbial and invertebrate community in the soil, which are vital for the sustainable establishment of plants. OM applied in field trials range from low quality, coarse and slow to compost OM (e.g. wood chips, hay, rice-straw) and more immediately available high-quality OM (e.g. sewage sludge, compost, animal manure) to processed biomass (biochar, charcoal).

These different types of OM have additional advantages specific to phytoremediation: slow-rotting, coarse materials enhance the hydrological properties of fine-grained, compacted mine tailings (see hydro-geochemical stabilisers) over several seasons. On the other hand, higher quality OM improves the structure of sandy mind waste, decreases their mechanical compaction and promotes substrate aggregation, aggregate stability and water retention, but is exhausted more rapidly. Both can be applied in combination and over time, litter produced *in situ* will eventually replace the (potentially repeated) addition of OM in sustainable remediation.

Among the ‘processed’ OM used in remediation are (activated) charcoal and biochar. Long-lasting and slow to degrade, they (mostly) belong to the category of low quality OM. Both have the capacity to adsorb or absorb potentially toxic metals and (temporarily) remove them from pore water, provide high cation exchange capacity (CEC) and hence support the regulation of nutrient supply to plants.

Biochar has attracted much research attention as a cost-effective and multi-functional soil conditioner, as it also works as long-term carbon store for climate change mitigation purposes. Biochar is produced by pyrolysis of biomass feedstock, such as forestry or agricultural crop residues (e.g. various straws, stems, husks, bark), biological wastes (anaerobic digestate, sewage sludge, manure) or biofuel plants (e.g. miscanthus). The pyrolysis process in itself can be used to generate electricity and for space heating, adding to the sustainability of biochar.

Biochar has a well-developed pore structure that provides a very high surface area with negatively charged functional groups that interact with metals in a variety of ways (inner-sphere and outer-sphere complexation, electrostatic interaction, surface precipitation, ion exchange), thus making them less mobile. In addition, biochar mixing with acidic mine spoil increases the pH, leading to a reduction in solubility of many metals and their precipitation. At relatively low dosage (2.5-8% biochar) it has been shown to significantly reduce technosol (soil) bulk density, improve pore structure, nutrient retention, water holding capacity, aggregate formation and hydraulic conductivity. The latter two are not only important for successful establishment of plant communities but also have the potential to reduce slope erosion. The OM biochar introduces to the soil ranges from readily available, unstable organic compounds that provide a usable energy source for microorganisms (MO) to relatively long-lasting, stable compounds that inhibit OM mineralisation. Biochar applications to mine spoil can also promote the abundance and diversity of soil MOs by providing a habitat in the large porous structure that affords protection from desiccation and predation. Overall, the addition of biochar to mine spoil has positive effects on soil condition, metal toxicity, plant root development and biomass. Biochar may also be used in combination with hydroseeding of slopes (see Section 5.5.4.1 [91]). The specific qualities of biochar produced from different feedstocks and pyrolysis conditions affect its properties and this, along with the application rate [87], should be carefully considered at the detailed design stage.

Microorganisms: the soil microbiome, composed of bacteria and fungi plays important roles in maintaining favourable soil conditions, plant health and hence in phytoremediation. Soil MOs decompose organic matter and provide biologically available nutrients, they change the physico-chemical properties of soils, including pH and redox potential and fix metals within their cells and mycelia. MO represent biomass that adds organic matter upon death, and they enhance plant biomass production through symbiotic relationships.

For example, filamentous fungi support the (micro)nutrient supply for plants and adsorb metal ions (e.g. Cu, Co, Cd, Zn, Pb) to their tissue, making them less biologically available and reducing the toxicity of contaminated soils. Some arbuscular mycorrhizal fungi and rhizobacteria release glycoproteins or polysaccharides that bind soil particles and facilitate aggregate formation, hence improving the structural stability of soils. Rhizobacteria actively colonise plant roots and strains that have been shown to have positive effects on plant growth in metal-contaminated soils include *Achromobacter*, *Arthrobacter*, *Azotobacter*, *Azospirillum*, *Bacillus*, *Enterobacter*, *Pseudomonas*, *Serratia* and *Streptomyces spp.* Equally, the addition of ericoid mycorrhizal fungi to overburden of a former kaolinite mine supported the establishment of heather, a key component of heathland. Even though the importance of soil MO to plant health is widely acknowledged, inoculation of seedlings with or soil applications of MOs for phytoremediation purposes showed various degrees of success in field and greenhouse trials and should only be considered in combination with other amendments, rather than as sole measure.

The hydro-geochemical stabilisation of mine wastes may also be achieved with microbial-based bioremediation (MBB). As metal/loids are elements and cannot be degraded, MBB relies on the generation of oxides or carbonates that result in the surface complexation or precipitation of metal/loids. For example, some metals form stable carbonate compounds (e.g. $CuCO_3$, $PbCO_3$, $CdCO_3$) and the production of calcite by ureolytic bacteria introduced to mine waste can support their formation through co-precipitation. However, the requirements of carbon sources for and long-term survival of added bacteria and the stability of the formed compounds under changing physico-chemical conditions is still subject to research. There is some evidence that arbuscular mycorrhizal fungi binds and immobilises metals in soils.

Chemical compounds: the biological availability of elements is often a limiting factor in remediation by phytoextraction and phytomining, which can be improved through soil application of liquid synthetic chemical compounds. Most widely used compounds in field applications include ethylenediamine tetraacetic acid (EDTA), ethylene glycol tetraacetic acid (EGTA) and sodium dodecyl sulfate (SDS) [65]. These compounds are chelating agents that strongly complex (bind) metals withing the soil solution. Their complexing strength out-competes weaker associations, for example adsorption to particles, thus maintaining metals in solution. For example the uptake of Cu, Zn, Pb, Ni and Cd has been shown to increase in the presence of EDTA in controlled experiments and has been associated with the direct uptake of the metal-EDTA complex by the root system. However, there is evidence that EDTA, EGTA and SDS are exhibit toxicity towards soil microbes and some agricultural plants and impair soil enzyme activity. In addition, these compounds are stable in the soil for many months, so that their effect on the desorption of metals and dissolution of minerals can continue in the dormant season and contaminate groundwater [65]. Therefore, the dose and timing of chemical compound applications need to be carefully designed with consideration of potential adverse effects.

5.5.2 Microbial Bioremediation

In addition to the contribution MOs can make to phytoremediation, the toxicity of redox-sensitive metal/loids species may be lowered by utilising the oxidising or reducing faculty of specific MOs.

For example, the soluble oxyanions arsenite (AsO_3^{3-}) and arsenate (AsO_3^{4-}) are present in many areas affected by metal mining, whereby the former occurs in the more toxic oxidation state As(III) and the latter as less toxic As(V). Some prokaryote bacteria have adapted to grow in arsenic-contaminated environments and utilise As(III) oxidation to gain energy by simultaneously reducing oxygen, nitrate or chlorate. Among these, the heterotrophic *Ralstonia sp.* and *Acinetobacter junni* have been isolated from mine site soils and sediment, respectively, while others, such as the facultative chemolithoautotrophy *Thiomonas sp*., and the heterotroph *Leptothrix sp*. occurred in mine waters [92]. Other applications of bacteria in the detoxification of mine wastes include the reduction of the highly toxic chromium species Cr(VI) to Cr(III) by a wide variety of bacteria, including species of *Bacillus*, *Aeromonas*, *Pseudomonas* and *Enterobacter* [59].

Although microbial remediation techniques have the advantages of cost effectiveness, efficiency, sustainability and absence of secondary pollution, they are susceptible to changing environmental conditions, in particular pH, the availability of water and redox potential. According to [61], they are more suitable to soils with less severe surface contamination, such as land surrounding mine sites that suffers from secondary pollution, rather than heavily contaminated mine spoil and tailings.

5.5.3 Constructed Wetlands

Settling ponds and cascades through which adit drainage flows before joining natural water bodies capture some of the dissolved metal/loids in mine waters through oxidation, precipitation and co-precipitation. A prominent example of a constructed, two-tier settling pond from the 19th century is the area outside Blanchdown Adit, Devon Great Consols Mine in the Tamar Valley, Devon, which is filled with a thick layer (several metres) of ochre made up of iron oxyhydroxide(sulfates) and co-preciptiated metal/loids rich in arsenic and copper (unpublished data). Outside the adit of nearby Dingdong Mine, a similar ochre layer has formed naturally on level ground by the riverbank. Further afield, iron-rich acidic mine waters often form natural cascades or terraces of precipitates, in which acidophilic MOs accelerate the oxidation of iron, arsenic and other redox-active elements and contribute to the removal of metal/loids from solution through precipitation. A well studied example of this is the acidic, arsenic- and sulfate-rich effluent from Carnoules mine tailings in the south of France [93, 94].

The natural presence of acidophilic protozoans in acid mine drainage can be utilised in constructed wetlands to encourage metal/loid (co-)precipitation and sedimentation [59]. The constructed wetlands more often applied in the wastewater treatment industry can be adapted with metal-tolerant macrophytes (aquatic plants). While hyperaccumulation among macrophytes is not yet well researched, their role in facilitating co-precipitation of metal/loids with iron oxides and carbonates has been more widely reported [59] and can be ascribed to similar processes to those associated with microbial-based bioremediation. A range of microorganisms are active in wetlands, including those naturally present in the mine drainage, thus aiding bioremediation processes. In addition, the physical slowing of water flow around macrophytes in wetlands promotes coagulation and the settling of particles and flocs, thus aiding the removal of dissolved metal/loids through sedimentation, while also aiding evaporation and evapotranspiration.

Few full-scale applications of constructed wetlands in association with remediation of contaminated land have been reported and questions about the longevity of macrophytes and the time-scale for excavation of precipitates remain unanswered. Nevertheless, where suitable level ground is available, a wetland could be constructed that intercepts AMD seepage from contaminated mine sites with the aim to reduce contamination reaching natural surface waters.

5.5.4 Physical Erosion Control

The erosion of mine spoil and tailings presents three major challenges: (i) export of contaminated material into the wider environment, (ii) exposure of fresh material to weathering and (iii) impeding of vegetation establishment. In some cases, notably riverbanks and steep slopes, physical means of controlling erosion may have to be installed to stabilise the ground before or simultaneously with the implementation of phytoremediation approaches.

5.5.4.1 Slope Stabilisation

Slopes at faces and sides of mine spoil heaps may prevent their effective colonisation with plants, as lose material erodes, water runs off and soil amendments, seeds and seedlings accumulate at the base of the slope. In addition, footfall on abandoned mine sites that are frequented by wild animals or people increases slope erosion. Hence, some mitigation measures that reduce footfall and slope erosion and can be used in combination are summarised here:

- Fencing can be effective in controlling footfall, although some wildlife and determined individuals will overcome physical hurdles.
- Cuttings of dense, evergreen, spiny vegetation, such as gorse and holly, may be obtained readily from nearby site perimeters or moorland management and placed on slopes, starting from the base, working upwards. The spiny branches interlock and present unattractive ground for foraging or recreation, increase surface roughness, trap particles and provide some protection against erosion caused by wind, precipitation and freeze-thaw. Gradually, degradation and composting will open 'clearings' amidst the brush that may be naturally colonised over time.
- Woven brush matting, wicker mats, erosion control blankets (straw, coir) and other biodegradable geomembranes fulfil similar functions to vegetation cuttings. They may be used in combination vegetation cuttings, soil amendments and seeds or seedlings. Although they require firm affixing to slopes with pegs and may at first look unsightly, they can support establishment of pioneer vegetation within the first season.

While covering slopes and preventing footfall addresses some basic problems of mine spoil heaps, the occurrence of slope failure and, to some extent, gully erosion are caused by the hydraulic head within the heap. Measures that reduce the infiltration of water and groundwater table within spoil heaps are important measures that also decrease the leaching potential of metal/loids from mine spoil. In this context, the hydraulic control measures discussed for site perimeters in Section 5.5.1.1 can be considered by using metallophyte species of willow and poplar. Furthermore, the revegetation of the top of spoil heaps discussed in Section 5.5.1.2 will contribute to reducing infiltration through evapotranspiration, as well as wind erosion that adds lose material to slopes. In some cases, more traditional agricultural drainage works may be indicated to deflect run-off from higher ground or lower the water table on site.

The design of technical slope stabilisation measures is primarily a civil engineering task, and much can be learned from the stabilisation of road cuttings and retaining structures. Kil *et al* [95] combined the civil engineering knowledge on slope stabilisation with plant-based mitigation and identified the parameters most important for hydroseeding applications as those that describe:

- topography (slope angle, height, length, aspect, curvature),
- geology (ground condition, seepage water),
- climate (rain intensity and volume),
- substrate physics (porosity, soil hardness, bulk density, soil texture, tensile strength, hydraulic conductivity),
- chemistry (pH, organic matter, salinity),
- vegetation (diversity, coverage, structure).

Hydroseeding is the spraying of a water-based slurry of seeds, nutrients, mulch (cellulose, plant fibre) and other amendments over soil that is to be re-vegetated and stabilised. The wet slurry has a higher mass than the drier substrate it is applied to and therefore, only a shallow layer can be applied to slopes and a strong binding agent that resists rainfall until vegetation roots have anchored the soil beneath is necessary to include in the slurry.

Widely used in the rapid establishment of lawns and erosion control in the construction industry, hydroseeding has also been applied to mine waste in the Cornish China clay industry for several decades and with varying degree of success [96] and more recently in greenhouse trials and small-scale pilots on contaminated mine spoil [91]. Important lessons learned from phytostabilising China clay and alkaline gold mine tailings include the success of grass/legume mixes (e.g. *Avena sativa*, *Festuca rubra*/*Trifolium repens*) and harvesting native, local seedbanks for hydroseeding stock [71, 96].

However, hydroseeding soil and relatively inert China clay waste does only partially prepare for the challenges of plant establishment on heterogeneous metalliferous mine spoil, for which limited examples exist in literature. More research and field trials are required, for which Southwest England may provide ample sites. Hydroseeding lends itself to the incorporation of additional amendments that address the specific challenges of metalliferous mine spoil (e.g. biochar, lime) covered in Section 5.5.1.4. In practical terms, a wide range of binders and mulch products used with different seed combinations are on offer from hydroseeding companies in the UK and relatively easily established germination greenhouse trials of mine waste/hydroseed mixtures could inform the design of field trials. The PhD thesis of Heather De-Quincey on the design of a hydroseeding mix to stabilise mine waste [97] is highly informative with respect to materials that provide mulch, adhesives (hydrocolloids), nutrients, minerals, organic matter, soil conditioning (biochar) and vegetation and practical considerations should be consulted if this method of initiating phytoremediation is considered.

5.5.4.2 Surface Run-off Management

Seepage of from mine spoil heaps and surface run-off are sources of acid mine drainage (AMD) common to many legacy mine sites in the Southwest. During periods of heavy rainfall, AMD reaching water bodies may lead to a spike of dissolved and particulate metal/loid inputs that result toxic impacts on the ecosystem.

Surface infiltration that leads to seepage can be reduced with phytoremediation techniques described elsewhere (Section 5.5.1), as well as with drainage work that prevents run-off from higher ground entering contaminated areas. In order to manage run-off from mine sites, mitigation measures more typically applied in flood management can be adapted to suit the topography and hydrology of abandoned mine sites. Examples include:

- Ephemeral seepage paths of AMD emanating from spoil heap slopes occurring during rainy periods often cause small-scale gully erosion. Their flow velocity and particle loading may be mitigated by constructing 'leaky dams' at the base of the slope. For this, locally sourced natural materials are suitable, such as low woven panels of hazel or willow cuttings staked into the mine spoil. These can be fortified upslope with denser branches of gorse or heather.
- Fine-grained mine tailings deposited in constructed lagoons or valley bottoms are typically of low permeability and hence prone to the pooling of rainwater and AMD. Such retention pools can fulfil some of the important functions of settlement pools (trapping of sediment, evaporation) and constructed wetlands discussed in Section 5.5.3.
  Existing areas of pooling water identified during periods of high rainfall can be enhanced by (i) protecting perimeters from erosion, (ii) raising or slowing the overflow and (iii) deepening or extending. This can be achieved by emplacing stone, coir or straw rolls, as well as establishing vegetation along the perimeters. If the site topography permits, new settling pools may be established using leaky dams in preferential flow paths towards lower ground or by emplacing lengths of coir or straw rolls held in place by stone rows.
  On some sites, machinery may be used to excavate settling pools or create scrapes along water courses to slow AMD run-off. However, the disturbance of compacted mine tailings should be approached with caution, as it risks erosion and the mobilisation of toxins.
- Level areas on top of coarsely grained mine spoil heaps may develop preferential flow paths for run-off, which may cause gully erosion on slopes. It not desirable to retain water on mine spoil with more than poor permeability because the infiltration increases AMD generation and building of a hydraulic head that risks

slope failure. Therefore, mitigation measures may be limited to re-directing water flow away from exposed and steep, to less vulnerable slopes, for example those that are already vegetated, are shorter or have a shallower profile. For this, the emplacement of natural materials is preferable to mechanical drainage work that disturbs mine spoil, because coarse grained mine wastes have zones of compaction and chemical cementation that are of lower permeability and erodibility.

5.5.4.3 Water Course Management

Nature-based management and restoration techniques for rivers and streams provide some solutions that can be adapted for mine sites. For reasons outlined in Section 5.5.4.2, the disturbance of mine waste itself should be avoided to prevent the acceleration of AMD mobilisation and erosion. Hence, mechanical grading, the creation of scrapes and floodplains and similar measures that directly impact mine spoil or tailings that line water courses, are not covered here.

At many legacy mine sites in the Tamar Valley, mine wastes form the banks of stream and rivers directly. Examples include tailings at New Great Consols through which Luckett stream flows, ochre deposits from Blanchdown Adit through which Wheal Emma stream flows (Devon Great Consols), and the Gawton mine spoil above the Tamar estuary near Bere Alston. The protection of riverbank mine wastes from erosion during spate flow events and tidal inundation is of particular importance to protect the benthic environment from smothering, the toxic effects of solids and to prevent further mobilisation of metal/loids into interstitial and surface waters. Some options include:

- River flow at the mine site can be slowed using a whole catchment approach to natural flood management upstream. This includes measures that retain water in the landscape and involve sustainable drainage solutions for urban areas and roads, changes in land use and farming practices, managing water connectivity and conveyance, planting native woodlands and providing water storage through wetland and floodplain restoration [74, 98]. Benefits include improvements in pollution export to water courses, in particular from roads and urban areas [99]. Closer to rivers and streams, possible measures include the introduction of beavers to create natural dams and riverbank vegetation (e.g. willow species), the construction of leaky dams (check dams) for small or ephemeral tributaries and drainage channels, and in-stream cascading pools and meanders. While stakeholder engagement, finance and access to land can be major challenges, living native plants (e.g. willow, sallow, hazel) used in this context may generate revenue [100]. Many catchment-based schemes are underway or have been delivered by the Environment Agency in collaboration with Rivers Trusts and Wildlife Trusts.

- Within mine sites, protection against riverbank erosion may be achieved with hurdles or screens made from natural materials (e.g. brushwood fascines and mattresses, willow hurdles). They may be supported with rock rolls or coir rolls at the toe and backfilled with flexible natural materials, such as coir or straw rolls, brush matting or wattles to provide additional capacity for trapping of sediment. In locations where stream velocities cause high sheer strengths, flexible rock rolls can be used to shore up sections of riverbanks prone to erosion. Rock rolls trap fine sediment and the establishment of vegetation can be encouraged when combined with pre-seeded natural geotextile rolls or mats.
  A range of nature-based solutions are commercially available and case studies presented on company websites can provide inspiration for the combination of different measures along river sections with varying characteristics [101-103].

5.5.5 Isolation or Detoxification of Contaminated Structures

Some structures and waste materials at legacy mine sites in the Southwest are highly contaminated. These include the arsenic-rich efflorescence on arsenic calciners, labyrinths and associated flue and chimneys, as well as concentrated metal/loid pollution in precipitation lagoons and launders installed at adit outflows or for metal recovery.

Exposure of such structures to the elements risks weathering and consequent release of contaminants into the wider environment, including ground and surface waters. Hence, the decontamination of such structures is desirable, but incurs considerable expense, part of which would be associated with the handling, removal and disposure of hazardous materials. Attempts to decontaminate *in situ* by removal of superficial efflorescence, for example through pressure washing, is unlikely to be successful in the long term, as efflorescence will recur. The arsenic labyrinth at Botallack (National Trust) was dismantled brick-by-brick, decontaminated *ex situ* and subsequently re-assembled. This removed the mortar and cleaned the bricks that had been impregnated with arsenic fumes during the processing of ores in the late 19th century and was necessary to prevent the recurrence of toxic efflorescent salts within seasonal wetting-drying cycles and grant safe access to visitors.

Where such thorough decontamination is impractical, the isolation and stabilisation of structures should be considered. This may involve:

- fencing at a secure distance with the aim to exclude the public and (medium and large sized) wildlife from getting in direct contact with structures and prevent (accidental) damage and erosion,
- securing and stabilisation of structures to prevent further deterioration and water ingress that may enhance leaching of contaminants into soils and formation of efflorescent salts (e.g. repair or sealing of damaged structures, provision of shelter in form of free-standing roofs above structures),
- repair and monitoring of retaining walls of precipitation lagoons to prevent breaching and release of material into downstream water bodies,
- shielding with vegetation screens with the aim to reduce aeolian transport of dusts to surrounding areas, potentially using thorny species that also reduce the desirability to access the area.

5.6 Summary

The outcomes of Section 4 highlighted the complexity of sources and pathways at New Great Consols and hinted at the likelihood of each individual legacy mine site having quite unique characteristics. With some 150 closed mining facilities that cause serious environmental impacts in England and Wales it is unrealistic to assume that resources are available to fully investigate and understand all sources, pathways and receptors of contamination at each site. Even with the level of detail now available for NGC, questions about the above and below ground hydrology and the nature of mine spoil at depth remain open.

With the aim to provide a broad overview of possible interventions for land contaminated with metal/loids, remediation based on the source – pathway – receptor model in the context of legacy mine sites was introduced (Section 5.4) with annotated diagrams (Figure 5-1, Figure 5-2) and a summary table of important physical, chemical and biological remediation methods (Table 5-1). Among these, particular attention was placed on the benefits and limitations of nature based solutions (NBS) and green and sustainable remediation (GSR), as more environmentally and economically sustainable alternatives to more invasive, high-cost, high-maintenance and/or high-tech methods.

The collection of NBS/GSR strategies presented in detail in Section 5.5 is not exhaustive but covers a range of options that tackle diverse sources and pathways commonly encountered at legacy metal/loid mines in the Southwest. As such, it intends to provide background information that supports the selection of remediation interventions beyond the specific case of New Great Consols. One of the main limitations of NBS/GSR lies in their incomplete remediation. Demanding a shift in mindset to achieving amelioration, rather than perfection, the selection of strategies includes:

- management of site perimeters (5.5.1.1) with the aims to provide hydraulic control, wind break, visual amenity and/or phytoextraction, with potential added benefits for carbon sequestration, diversification of the rural economy and habitat creation,
- phytostabilisation (5.5.1.2) of mine tailings and spoil dumps, aimed at reducing erosion and retaining metals in the rhizosphere, providing details of mechanism, examples of suitable plants and details of soil amendments (5.5.1.4) required to establish plants on challenging substrates,
- phytoextraction (5.5.1.3) of shallow and light to moderately contaminated ground, such as farmland that has received atmospheric deposition of contaminated dust or stack emissions,

- microbial bioremediation (5.5.2) that employs a wide array of microorganisms capable of detoxifying contaminated environments by oxidating or reducing chemical elements from more to less toxic forms, including arsenic oxidising and chromium reducing bacteria,
- interventions that straddle the physical and biological realm, including constructed wetlands (5.5.3) that settle particles and provide areas for iron oxidation and co-precipitation of metal/loids, slope stabilisation with living or dead plant matter (5.5.4.1), hydroseeding, and the control of surface run-off and river bank erosion using natural materials,
- isolation of structures with the aim to prevent accidental damage that could lead to the accelerated spread of contamination.

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6 Interventions at New Great Consols

6.1 Aims and Scope

The aim of this Section is to provide a range of intervention measures as a basis for discussions with stakeholders, including landowners, the local population and Historic England. By combining the insights obtained in Sections 3 and 4 with the remediation approaches presented in Section 5, intervention options that are site-specific for New Great Consols (NGC) at Luckett are developed here with the objective to address the sources and pathways of diffuse metal/loid pollution to Luckett Stream using Nature Based Solutions (NBS) and Green and Sustainable Remediation (GSR) techniques.

6.2 Non-technical Summary

The main areas of concern at New Great Consols fall into the categories of (i) highly contaminated coarse mine waste slopes, (ii) fine tailings on level ground, (iii) riverbanks lined by tailings and (iv) unsafe remains of buildings.

With the aim to reduce the erosion and leaching of pollution from mine wastes, the areas of bare and thinly vegetated ground at NGC were identified for revegetation with soil improvement from largely locally sourced materials and plants propagated from those present on site. Because of the undulating terrain, slopes require additional measures to hold soil, seeds and plants in place, such as wicker hurdles and interlocking thorny branches placed on the base and slopes. Some control of run-off from higher ground onto slopes and the pooling of sediment-laden water is desirable to enhance the chances of revegetation and particle run-off from the site into the stream. Erosion control and successful revegetation also necessitates the reduction of compaction on flat ground and abrasion of sandy slopes by footfall, whether by humans or wild animals. For this reason, the exclusion of the public from the sites is proposed, alongside a campaign of engagement and outreach. The patchwork of interventions is summarised in Figure 6-7.

The limitations of the remediation interventions presented here are inherent in nature based solutions, which are seeking to reduce, rather completely stop pollution from entering the river. Furthermore, underground workings will not be affected by measures suggested here and some of the contamination in Luckett Stream arises further upstream in the catchment.

6.3 Areas of Concern: Overview

The legacy mine site New Great Consols at Luckett comprises of diverse mining wastes, structures and buildings in various states of dereliction that constitute sources of contamination as identified in Section 4. The main points of concern for remediation interventions are summarised here with reference to the map Figure 6-1:

- Around the remains of the treatment mill (TM) in the south of the site, the mine spoil dumps (MSD) feature a mix of rubble and coarse overburden on steep slopes. The area is vegetated with a canopy of birch and oak and undergrowth of shrubs, ferns and herbs. The highly contaminated, isolated area of finely grained whitish tailings (WT) to the northwest of TM is not vegetated (Figure 4-14).
- The arsenic processing complex comprises of the arsenic mill (AM), calciner row (CR), calciner flue (CF), arsenic labyrinth (AL) and calciner chimney (CC) (Figure 6-2, Figure 4-2 and Figure 4-3). Highly contaminated ground (Cu, Zn, As, Sn and Pb) surrounding the CR and leading south towards the AM appears to be infill of reddish-brown mine or calcination (ore processing) waste visible at surface between puny vegetation. This infill partially buries a row of structures a few metres south of the CR that, from their position and construction, can be assumed to be the remains of arsenic labyrinths (AL?). They appear to be connected to the calciners by ruined flues (CF?) on either end of the CR. The CR, CF, AL and CC are by nature of their former function impregnated with arsenic-rich fumes, leading to the formation of blooms of efflorescent salts at surfaces, which are potential pollution sources. The area to the north in front and below the calciners is partially vegetated (trees, shrubs, herbs), level ground bordered by a wall or mound to the north, beyond which the main mine spoil dumps (MSD) are located, forming several levels on the hill leading towards the valley floor.
- East of the CR are the south-north running remains of a water course or leat between the TM and its termination at the sluice to the MSD. The area to its east features undulating ground, excavations, shafts (ST) and the remains of an engine house (EH) among woodland vegetation and a grey, coarse grained, unvegetated, spoil dump (USD, Figure 6-3). The latter shows signs of human and animal footfall and erosion fans spreading onto the main mine spoil dump (MSD).
- The main MSD in the centre of the site (Figure 6-3, Figure 3-2) appears to comprise coarsely grained, sandy, grey wastes visible on unvegetated slopes on its northern face, overlain with reddish-brown, finely gained tailings that may have been deposited via the water channel from the TM, using the original spoil heap as base for sludge beds. MSD is partially vegetated with shrubs (gorse,

bramble, heather) on margins of open ground that features some mosses and scarce grasses. The unvegetated slopes show signs of footfall, gully erosion and fan erosion (Figure 4-4) and feature ephemeral springs after heavy rain.

- Further north in the valley bottom are layered white (WT) and red tailings (RT) deposits, located between MSD and the southern bank of Luckett Stream. The area is partially vegetated with woodland and shrubs along the riverbank and margins of the MSD slopes. Areas of unvegetated or intermittently vegetated whitish-grey, fine grained tailings (WT) are exposed and subject to compaction by footfall along tracks (Figure 6-4, Figure 4-5, Figure 4-6). During high rainfall periods, a relatively barren area of these tailing floods, forms an ephemeral pond (Figure 4-7) and overflows into the river via a ditch.
- Further east and north of the river are former sludge beds that are dominated by reddish-brown tailings (RT) at the surface (Figure 6-4). However, layering exposed by erosion at the culvert exit indicates that the sludge beds are heterogeneous at depth (Figure 4-8, Figure 4-9).
- North of the river, an engine house, other building remains and structures, an adit, fenced shafts and vegetated MSD are hidden among a canopy of birch, oak, as well as shrubs (gorse, bramble, hazel, Figure 6-4).
- To the west, a mix of white and red tailings crop out among low shrubs, high stands of bracken and birch trees. During high rainfall periods, an undulating, relatively barren area of tailings floods, forming an ephemeral pond with a clearly visible overflow to the river through eroded red tailings (Figure 6-4 and blue arrow on map in Figure 6-1).

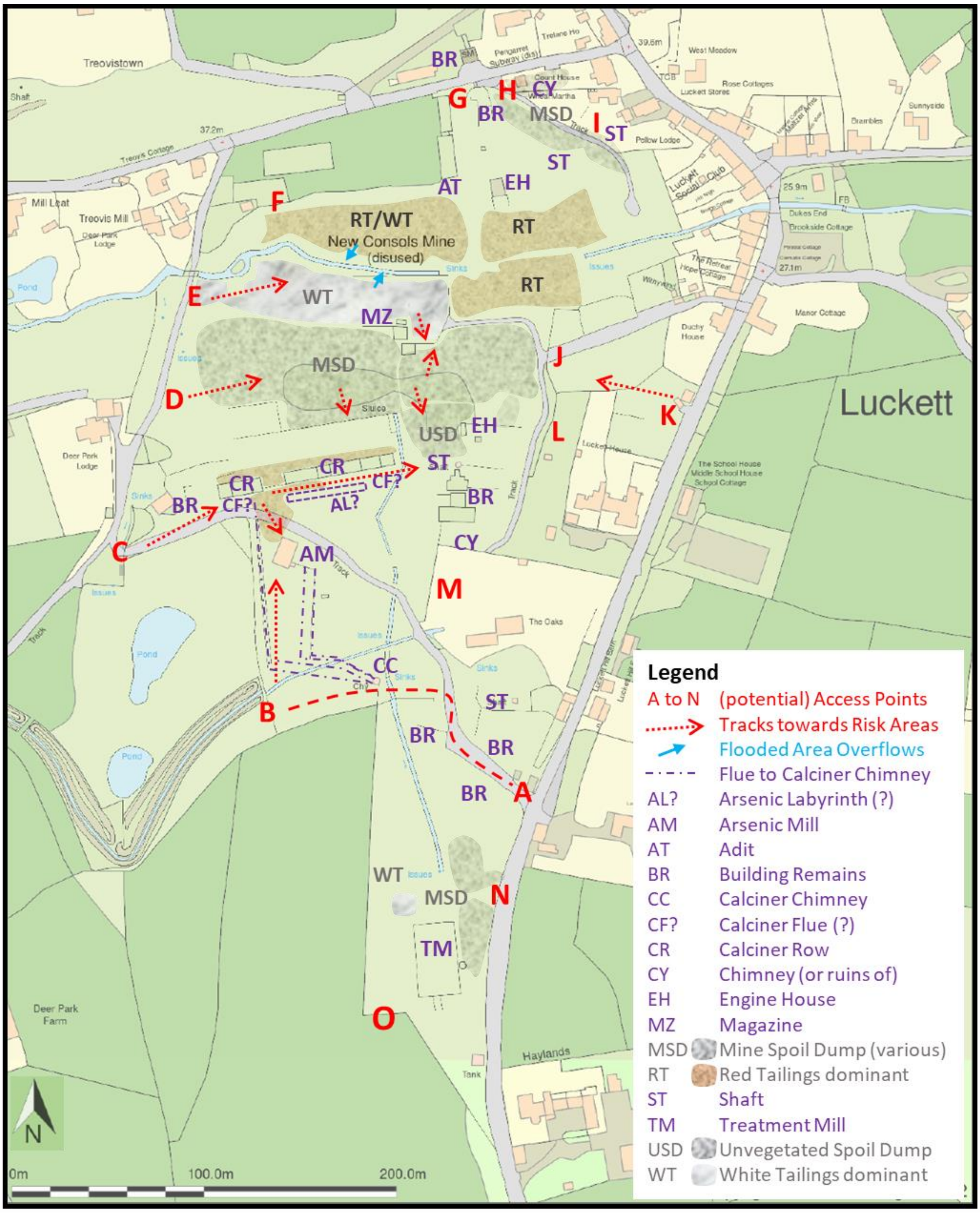

Figure 6-1 Map of mine waste areas, partially ruined remains of structures and buildings (Al to TM) and (potential) access points (A to O) on NGC. The approximate extent of mine waste areas (MSD, USD, WT, RT) are a composite of historic map records and walkover surveys. Location of AL and CF uncertain and flues to CC transferred from historic map. Map base as for Figure 4-28. © Crown copyright and database rights 2023 Ordnance Survey 100049047.

Figure 6-2 Appearance of the area around the calciner row (CR). Top row: the collapsed line of roofs is photographed looking east. CR detail: easternmost calciner, showing a sharp metal spike, efflorescent salts, rubble and a food container (arrow) on the ground (also see Figure 3-5, Figure 4-2 and Figure 4-3). Middle row: partially buried ruined building with arched openings on higher ground south of CR, with remains of channels and iron gates, potentially the calciner flue (CF?) leading to the arsenic labyrinth (AL?). Bottom row: area above CR and AL? (orientation marked by yellow arrows) accessible by site entrance C and level ground between CR and MSD. Abbreviations as labelled on map in Figure 6-1. Photos: C Braungardt 2022&23.

Figure 6-3 Photographs of the main mine spoil dump (MSD) and unvegetated spoil dump USD) and associated engine house (EH) and steep drop (shaft, ST) at NGC, with site access points A, C and D and a marker post for the Kit Hill Link Walk near the calciner chimney (CC). Labels as on the map in Figure 6-1. Photos: C Braungardt 2023.

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Figure 6-4 Images of predominantly white tailings (WT) to the south (s) and reddish brown and white tailings (RT/WT) to the north (n) of Luckett Stream, all accessible via track E in the west and J in the east, as well as from all northern entrance points. Top right: area prone to flooding on WT with overflow indicated by blue arrow. Bottom right: eroded overflow (o) into the river from an area on RT/WT that is prone to flooding. Abbreviations as labelled on map in Figure 6-1. Photos: C Braungardt 2023.

6.4 Site Access and Isolation of Receptors

The mine wastes at New Great Consols show visible signs of compaction and erosion caused by human recreational use, including mountain biking and dog walking (footfall). Most obvious are numerous tracks across the mine tailings in the valley floor, footprints on mine spoil dumps to their south and tracks around the calciner row and flue. Vegetation establishment is inhibited by compaction and repeated use of tracks and low-lying tailings tend to become waterlogged and flooded. On slopes and at the margins of mine wastes, erosion by footfall adds to aeolian, gravitational and fluvial erosion processes, all of which inhibit the establishment of vegetation and promotes loss of material to lower lying ground. Hence, footfall worsens contamination export to Luckett Stream and the surrounding area (Section 4.7).

Public access to the site may compromise the integrity of the mining heritage, key components of the scheduled status with Historic England and the UNESCO World Heritage designation. In this context, the footfall erosion of spoil heaps plays a role, as well as potential littering and inadvertent damage or deliberate vandalism of buildings.

Currently, footfall by humans and pets across the site is encouraged and/or accepted around the site perimeter (labels refer to Figure 6-1):

A---B: The Kit Hill Link Walk is clearly waymarked and traverses the site from the road leading into Luckett (A, Figure 6-3) past mine building remains (BR) and a fenced shaft (ST), passing closely by the calciner chimney (CC, Figure 6-3) and exits at the site boundary with Deer Park Farm (B).

Evaluation: The area is generally well vegetated, no direct contact with mine waste on the path is evident and risk to walkers staying on the path can be deemed acceptable. However, of concern are the level of contamination on and near the calciner chimney, the presence of moderately contaminated bare ground near the path and the branching off of tracks leading along the line of the arsenic flue to the calciner chimney towards the arsenic processing complex (CR, CF?, AL?, AM, CC, Figure 6-2).

Specific additional mitigation measures: It is desirable to fence both sides along the route of the permissive Kit Hill Link Walk in such a way that recreational users, their children and pets cannot divert from the path, for example with stockproof fencing secured with barbed wire.

C: The southeastern entrance to NGC branches off the track that leads up from Deerpark Lodge. At the gateway a sign details the landowner's (Luckett Heritage CIC) conditions for accessing the site and a reminder to clean up after dogs (Figure 6-3). The signs give the impression that it is permissible to use the site for recreational activities, such as dog walking.
Evaluation: The area is well vegetated at this point but leads directly to the arsenic processing complex.

D: A narrow track opposite Deer Park Lodge leads onto the level ground at the top of MSD (Figure 6-3). The entrance point leads from woodland through a trodden-out gully of spoil onto a patchwork of open ground (bare spoil, mosses, heather) and shrubby vegetation (gorse, bramble, birch) that stretches from the western to the eastern extents of the site (points J and K) and provides access to the unvegetated slopes of the MSD and USD.
Evaluation: this MSD is one of the main sources of contaminated leachate and particles to the river. Therefore, it is a focus of NBS interventions that require the minimisation of disturbance and footfall to avoid erosion, compaction and allow the establishment of vegetation (Section 5.5). Furthermore, the features nearby present physical and toxic hazards.

E: Across the small stream leading from the lakes at Deer Park Farm to Luckett Stream, a track leads onto the WT between the MSD and the southern bank of Luckett Stream. The area is partially vegetated with woodland and shrubs along the margins with the river and the slope of the main mine spoil dump (MSD). Areas of unvegetated or intermittently vegetated WT are exposed and subject to compaction along tracks by footfall (Figure 6-4).
Evaluation: As for D.

F: The boundary between NGC and the garden at the northwestern corner of the site is not secured by fencing. Site access from the lawn area of the garden is on level ground into a wooded strip (birch, oak) that opens to highly contaminated RT/WT that have been seen to flood in intense rain events.
Evaluation: Accidental straying onto the site from private land affords undesirable access to areas subject to NBS interventions (as for D).

G: Rough, partially vegetated ground among ruined buildings associated with the mining legacy affords access to the northern part of the site from the road.
Evaluation: Potential for unstable ground or buildings and access to all parts of the site are undesirable regarding the potential interference with remediation interventions (as for D). It also provides access to the entrance and exit portals of the culvert, which at times flows strongly (see Figure 4-10).

H and I: Access from the road via a stile and farm gate (H) to the Wheal Martha area in the north of the site. Nearby shafts and engine houses are secured by fencing and the track leads to lower ground north of Luckett Stream. As the case of F, open access from a private garden (I) is evident in the vicinity of an old shaft (ST).
Evaluation: As for D and G.

J: The eastern entrance to the site passes dwellings and a children's playing field and connects with a track that leads around the engine house (EH), into the arsenic processing complex, onto MSD, USD and onto the stream and tailings area in the valley bottom.
Evaluation: As for C, D and G.

K: Just south of J, a track leads from the road past a low building and onto the site.
Evaluation: As for C, D and G.

L, M, N and O: General note that fences around gardens of houses and of fields adjacent to NGC may not pose a secure barrier to access. Equally, at some places along the road, fences are easily overcome.
Evaluation: As for C, D and F.

To mitigate against these matters and achieve maximum efficacy of remediation interventions, the unregulated and uncontrolled access to NGC should be discouraged, with measures (illustrated in Figure 6-5), such as:

- secure fencing around the whole of the site perimeter and along the permissive footpath (Kit Hill Link Walk),
- secured gates at remaining access points (H, J),
- establishment of dense, evergreen and thorny vegetation at existing public access points that are due to be closed (C, D, E, G, J, K) and around the calciner row and isolated white tailings in the south of the site, with the aim to further discourage access and provide erosion control through wind break effect,
- discussion and agreement with adjacent landowners to securely fence off the common boundary (F, I, L, M, O) and encouragement to plant windbreak vegetation (dense, evergreen) along the fence line.

In addition, the calciner row, flue and labyrinths, as yet unsecured engine houses and shafts and the isolated white tailings in the south of the site should be secured separately and additionally. This is particularly important in case that secure fencing around the whole of the perimeter is not implemented.

Risk areas identified during site walkover surveys and sampling campaigns associated with this report and the approximate routes of fence lines are outlined in Figure 6-5. However, more detailed site surveys are necessary to identify potential further risk areas and the exact line of fences.

The vegetation used on site should ideally be sourced from native stock already present at NGC. Suitable species include bramble and gorse, as they have encroached on the margins of mine spoil and tailings and form an uninviting thicket. Propagation by layering (bramble), semi-ripe wood cuttings (bramble, gorse) and seed collection (gorse) from specimen at NGC can be undertaken in autumn. The preparation of mine spoil and tailings for revegetation is discussed in Section 6.6.2.

In order to make the exclusion of the public a successful endeavour, stakeholder engagement and public education is paramount to develop compliance through understanding the importance of remediation interventions. The UNESCO and Historic England designations of the site merit that ongoing public engagement should be considered, for example via public display boards, occasional guided tours for small groups and an interactive website that provides access to information on the mining history, stories, images of the site, contamination and remediation measures.

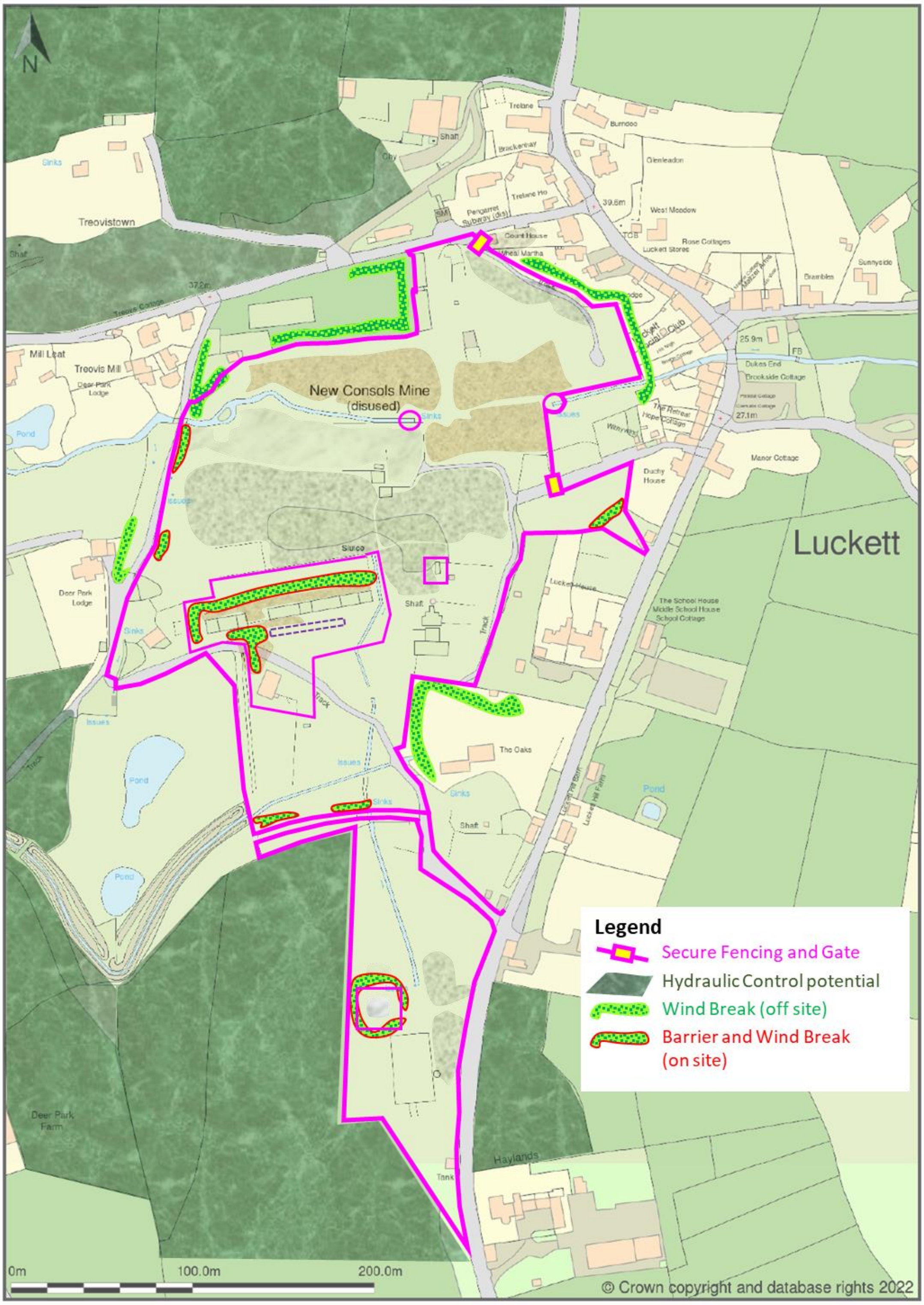

Figure 6-5 Approximate outlines of i) secure new fencing and access gates proposed for the perimeter of NGC and specific areas within NGC (exact routes of fence lines is subject to surveying), ii) areas with potential hydraulic control tree plantations, iii) vegetation wind breaks and screening on and off site. Map base as for Figure 4-28 © Crown copyright and database rights 2023 Ordnance Survey 100049047.

6.5 Contaminated Structures

Efflorescent salts on structures within the arsenic processing complex may contribute significantly to the export of contamination, as they are solubilised during periods of high rainfall and transported in leachate. The least exposed parts of structures show the most abundant and thickest crusts of efflorescence, while more exposed outside walls may be ‘washed’ more frequently by rainfall and exhibit thinner layers of efflorescence.

Efflorescence is the product of water ingress into brickwork and mortar, where it dissolves constituents (sulfates, carbonates) to form metal/loid enriched brines that migrate to the surface, where crystals are formed upon evaporation. Therefore, the prevention of water ingress into structures is the most effective way to mitigate against this source of pollution. Furthermore, the protection of structures against water ingress supports the preservation of the industrial heritage at NGC.

Water ingress can be limited by:

- constructing a roof with sufficient overhang on the calciner chimney (CC in Figure 6-1), without impeding ventilation,
- maintaining the metal roof on the arsenic mill (AM n Figure 6-1) in good order (AM was not inspected internally),
- constructing a roof with sufficient overhang above the calciner row (CR in Figure 6-1), or as an alternative, the reconstruction and waterproof sealing of the calciners themselves.

Once water ingress has been minimised, the existing efflorescent salts on the structure of the CC and CR and on their base should be removed. Collected materials are to be treated as hazardous waste.

The back walls of the calciners are built into the ground or buried by mine or calcination waste and exhibit efflorescence, which can only be mitigated by excluding water seepage from the soil into the back of the building. Measures against this would involve the installation of damp-proofing or tanking and drainage work used in civil engineering and construction, with considerable disturbance of ground.

The exact position and extent of the presumed calciner flue, arsenic labyrinth (CF and AL in Figure 6-1) and parts of its connection to the CC are unknown and at least partially buried in mine or calcination waste and/or soil and heavily overgrown with impenetrable vegetation, such as bramble. No efflorescence was obvious on the exposed parts of the AL, although can be assumed to exist, given the former function of the buildings. Water seepage from the ground into the structure is likely a main factor in the generation of efflorescence, if indeed present, and the construction of a shelter above these structures would probably have a limited mitigation effect while necessitating the disturbance of ground and vegetation. Tanking against water ingress would, as for the calciner row, involve major disturbance of ground and vegetation and lead to additional release of contamination.

Only brick-by-brick dismantling of structures, removal of all mortar, washing of bricks and rebuilding would entirely solve the pollution sources associated with the CR, CF, AL, AF and CC. This is unlikely to be feasible and as it mainly addresses arsenic and not copper contamination, may not be a priority for the main aim of this project.

Contractors tasked with any works around the arsenic processing complex must be made aware of the contamination status and toxic risks associated with the works and any works must be undertaken following comprehensive risk assessments, using appropriate PPE, applying measures that protect workers from metal/loid exposure and avoid the mobilisation and/or spreading of contaminants and damage to the buildings (also see Appendix Section 9).

6.6 Nature Based Solutions and Green and Sustainable Remediation

6.6.1 Hydraulic Control Outside NGC Perimeter

The interactions of water and oxygen with contaminated soils and spoil, as well as metal/loid ores in underground workings, have the potential to mobilise metal/loid contaminants and transport leachate to the river. Therefore, it would be desirable to limit water infiltration, run-off and shallow groundwater movement.

The hydrology of NGC below ground is unknown and underground workings and adits are likely to provide preferential flow paths that lead to the river. In this situation, the general principles of the depth of the water table and groundwater movement within undulating catchments have limited application. Nevertheless, the reduction of precipitation infiltration and enhanced uptake of water from the ground can be achieved by increasing the evapotranspiration on and around the site. Such planting has added benefits, for example reduction of aeolian erosion and screening (Section 5.5.1).

The New Great Consols site straddles the river valley and topographically occupies a ridge in the south and slopes up to a hill in the north. The planting of deeply rooted, fast growing species with high water demand upslope of NGC has the potential to exercise some hydraulic control by lowering the water table and reducing the overland flow from higher ground onto the site. The areas of land with potential for plantation of trees outside the NGC perimeter for hydraulic control are marked on Figure 6-5 and would also afford some wind protection from south-westerly and north-westerly quarters.

Plant-based hydraulic control is severely limited in this location by:

- uncertainties associated with the lack of field-scale trials in temperate climates,
- uncertainties regarding below ground hydrology at NGC,
- seasonal fluctuation in evapotranspiration rates (cessation in winter),
- dependence on landowners beyond NGC.

Hydraulic control plantations can provide diversification opportunities for landowners (e.g. biomass production and other silviculture products) and contribute to sustainability objectives (e.g. carbon sequestration, habitat creation). These benefits may provide incentives that merit taking the risks associated with the limitation of the method as remediation intervention and hence, could lead to a valuable case study if baseline and long-term monitoring is undertaken. In this context, the review by Cooper *et al* [74] is instructive.

The selection tree species and diversity for hydraulic control at NGC depends on the wider social, economic and environmental sustainability objectives of the project, which have been discussed in Section 5.5.1.1 and also include potential local factors, such as:

- traditional coppicing makes use of ash, hazel, oak, birch, willow or alder for the production of charcoal, firewood or traditional products, such as walking sticks and baskets, but not all would be suitable for hydraulic control,
- plantations for biomass relies on fast growing trees that could include willow and poplar species and also feature high water demand, but may suffer on slopes under drought conditions,
  hydraulic control can be effective using resilient non-native species, such as eucalyptus, which is widely planted in the Tamar Valley for horticulture,
- habitat creation and the provision of amenity benefits from native mixed species and mixed age plantations that develop into a natural woodland over time may be desirable; the trees and large shrubs already present on NGC include oak, beech, ash, birch, sycamore, mountain ash, apple, crack willow, hawthorn, hazel and elderberry.

In addition, plant-based flood control measures could be considered in collaboration with landowners for the whole of catchment, with the aim to reduce peak flow volume and velocity in the stream and hence, mitigate against bank erosion of mine tailings at NGC during peak flow conditions (Section 5.5.4.3).

Hydraulic control species, such as poplar and willow, could also be included in wind break planting on site, for example on the low ground north of the calciner row, where they may contribute to lowering the subsurface flow towards MSD and the valley bottom.

6.6.2 Phytostabilisation of Scarcely Vegetated Areas

As detailed in Section 5.5.1.2, phytostabilisation has a wide range of benefits that include erosion control and reducing water infiltration, which in turn reduces leachate formation and particle run-off to lower ground and water courses.

Barren and thinly vegetated surfaces feature strongly on mine wastes at New Great Consols and are often associated with compaction resulting from recreational use and steep slopes (Sections 4.3 and 6.3). Nevertheless, large parts of the mine tailings and spoil dumps are already partially vegetated as a result of encroachment from the surrounding landscape and natural succession on site. The early stages of vegetation development on NGC include lichen, mosses, bryophytes and grasses, which through the accumulation of organic matter lay the foundation for the establishment of ferns, bracken, ivy, heather and calluna, gorse, bramble, hazel over time. The distribution of these species and trees depends on the growth medium and therefore, the most successful and least resource intense approach to phytostabilisation would be one that encourages the plant community established on site to spread across as yet unvegetated areas and to accelerate the progression from early succession stages to full vegetation cover.

In Figure 6-6, the approximate areas currently thinly vegetated or entirely barren are outlined in red and numbered for reference in Table 6-1, which summarises vegetation types, cover and contamination status. Analysis of Table 6-1 suggests that the following species may be utilised in phytostabilisation:

- **grasses** are present on NGC tailings as third stage after lichen, mosses and bryophytes and species known to be tolerant to conditions prevailing in mine wate, such as *Agrostis capillaris, Festuca arundinacea* and *Festuca rubra;* grasses benefit substrate cohesion with the development of root mats and may be utilised through harvesting of seeds on site,
- **heather** and **calluna** species are calcifuges and well adapted to meagre and water-logged soils; their value on NGC is largely ecological, rather than as element of remediation; difficult to establish by seed; the planting of seedlings may benefit from mycorrhizal fungi inoculation,
- **common gorse** is a calcifuge, metallophyte, drought-resistant nitrogen fixer, forms an evergreen thorny thicket that is suitable as effective wind break and for erosion and access control; may be utilised through harvesting of seeds or propagation of cuttings from the site,
- **bramble** benefits from its spreading strategy that allows the parent plant access to better soil conditions than those encountered on tailings; it may be propagated by layering on humus soils at NGC,

- **birch** is calcifuge and well adapted to poor and water-logged soils and is widely distributed among tailings; birch will propagate naturally by seedlings falling among organic material and can be utilised by harvesting of seeds on site.

Successful phytostabilisation requires the creation of a suitable growing medium on the bare or partially vegetated ground, which can be achieved with a selection of the soil amendments detailed in Section 5.5.1.4. Although desirable for establishment of plants, the working in of soil amendments by tilling could mobilise contaminants from tailings and increase erosion (Section 5.5.1.4) and cannot be recommended.

Sustainable soils amendments that support phytostabilisation at NGC should be long-lasting, self-sustaining and provide a source of organic matter without tilling. Observations on site indicate that relatively small and thin natural accretion of organic matter on mine waste promotes succession and allows grasses to take hold. This indicates that even an organic layer of 5–10 cm in depth can provide enough growth medium to sustain grasses that can be sown (perhaps in combinations with legumes) in the first season and can be seen as an accelerator of natural succession, rather than provide rapid establishment of a plant community. Options for relatively thin layers of include:

i) Bare fine-grained and compacted tailings (areas 1, 7a and 8 in Figure 6-7) can be top-dressed with a mixture of low-quality biosolids (e.g. wood chips, hay, straw, biochar) and high-quality organic matter (e.g. well-composted animal manure), with the latter as a minor component (e.g. 20%). Over their long decay time, the low-quality OM will improve the texture and hydrology of the tailings.
ii) Bare sandy, coarse-grained mine spoil (erosion fans and slope areas 6, 7b,c&d in Figure 6-7) can be top-dressed with a mixture of high-quality and low-quality OM, with the latter as a lesser component (e.g. 30%). The high-quality OM improves soil structure by enhancing aggregation, which is important on slopes.

Over time, the presence of coarse OM and grasses will allow the migration of soil MOs and invertebrates from nearby vegetated areas, physically entrap leaf litter and seeds and progress naturally into a more diverse community.

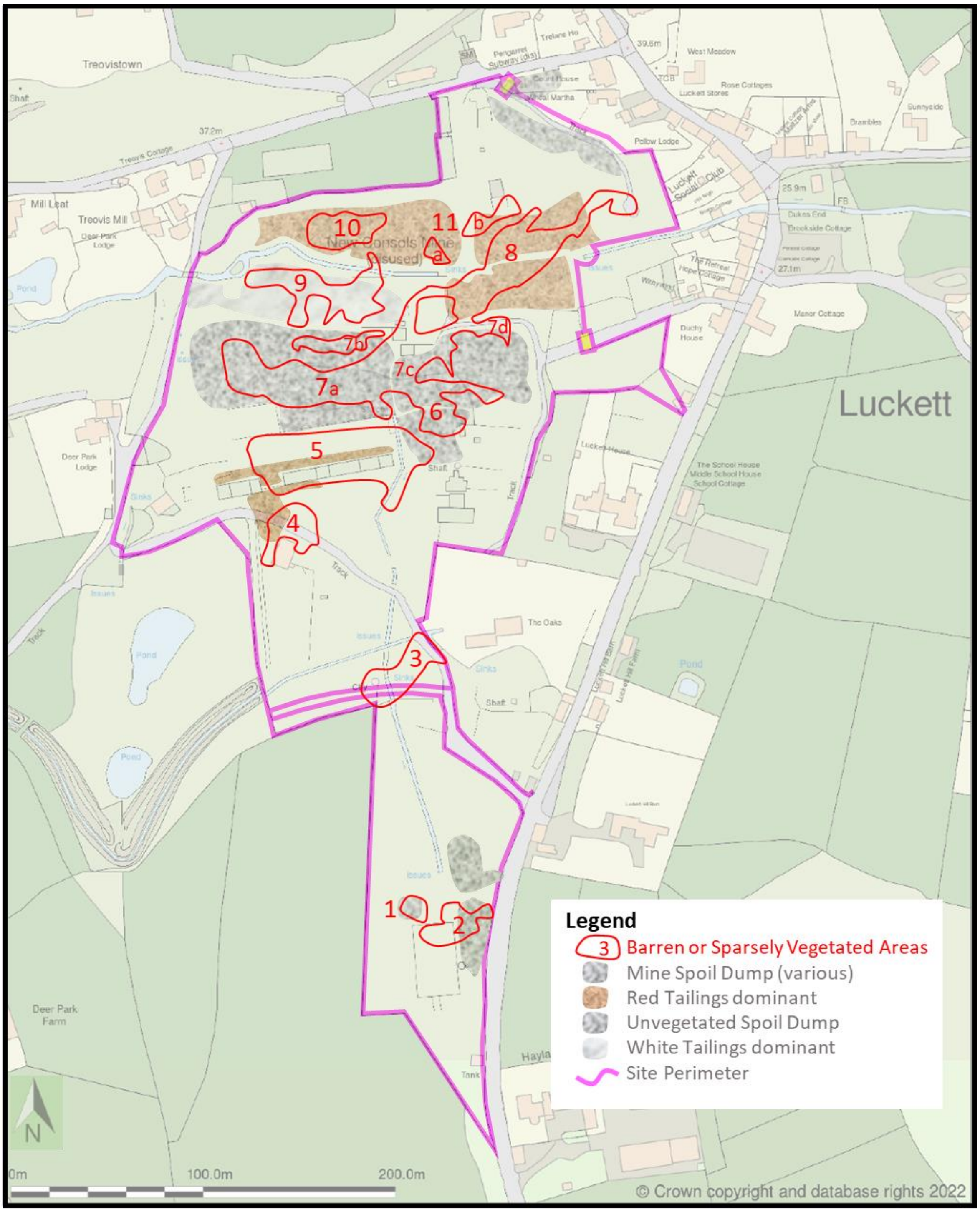

Figure 6-6 Outlines of thinly vegetated or bare ground and mine wastes within the site perimeter of New Great Consols in Luckett. Numbers are referred to in the text and in Table 6-1. Map base as for Figure 4-28 © Crown copyright and database rights 2023 Ordnance Survey 100049047.

Table 6-1 Thinly or unvegetated areas as outlined in Figure 6-6 with a summary of contamination status (highest quartile for the site) and description of substrate, vegetation type and cover.

Area	Contamination	Substrate	Vegetation Cover	Vegetation Type
(1)	As Cu Pb Sn W	whitish-grey silt	tailings bare, surrounded low vegetation, with shrubs and woodland canopy some metres away	mosses, grasses, ferns, gorse, birch
(2)	As W Zn	stony mound, leaf litter, some soil	thinly vegetated ground surrounded by woodland canopy	bracken, ferns, bramble, ivy, birch, beech
(3)	Cu Zn	dark humus soil, leaf litter	thinly vegetated ground under woodland canopy	ferns, nettle, bramble, hazel, hawthorn, rowan, birch, oak
(4)	As Cu Sn W Zn	patchy thin layer of organic matter over silty clay	no to partially thin canopy, open ground covered in shrubs with bare patches	bramble, ferns, hazel, birch
(5)	As Cu Pb Sn W	reddish-brown to purple silt, yellow-beige sand, leaf litter, thin soil in parts over rubble	south of calciner row: puny trees, shrubs around calciner: bare ground north of calciner row: puny trees, shrubs	lichen, mosses, ferns, bramble, gorse, birch
(6)	As Sn	grey sandy heap, some leaf litter	open, bare ground with steep slope, encroached by shrubs	lichen, mosses, grasses, ferns, heathers, bramble, gorse, with birch on margins

(Table 6-1 continued on next page)

(Table 6-1 continued)

Area	Contamination	Substrate	Vegetation Cover	Vegetation Type
(7)	As Cu Sn W	a: fine whitish silt b: sandy grey slopes c: fine reddish-brown silt d: sandy grey very steep slopes (consolidated)	flat ground largely bare, some early succession, rabbit digging, slopes (b) in large parts unvegetated, some shrubs slopes (d) largely bare all areas surrounded by shrubs and some trees	lichen, mosses, grasses, heathers, gorse, bramble, with birch on margins
(8)	As Cu Pb Sn W	fine reddish-brown silt, some whitish-grey silt	mottled vegetation cover with some barren ground and mounds among shrubs and under patchy, thin canopy	grasses, ferns, heathers, gorse, bramble, birch
(9)	As Sn	fine whitish-grey silt	bare ground on tracks and some openings, some early succession, rabbit activity, surrounded by shrubs and some trees along river	lichen, mosses, grasses, ferns, heathers, gorse, bramble, birch
(10)	As Pb Sn W	fine reddish-brown silt, some whitish-grey silt	mottled vegetation cover with some barren ground and mounds among shrubs and thick stands of bracken with surrounding thin canopy	lichen, mosses, grasses, bracken, heathers, gorse, bramble, birch
(11)	moderate	fine reddish-brown to purple silt mounds	some areas of bare ground with early succession under thin canopy and among shrubs	lichen, mosses, grasses, bracken, bramble, birch, oak

If the ambition is a more rapid establishment of a plant cover, dressing with a deeper layer (some 50 cm) of topsoil on flat ground (areas 7a and 9) may be indicated. Depending on the quality and length in storage, introduced topsoil may require enhancement with either low- and high-quality OM (or both) and OMs (e.g. mycorrhizal fungi, rhizobacteria). Harvested seeds of grasses, heathers, gorse and birch at NGC can be either grown into seedlings (or from cuttings), the growth medium inoculated with OMs and planted out, or sown into the amended topsoil on site.

The use of amendments that greatly lower the soil acidity (e.g. lime) should be avoided because of the high concentrations of arsenic at NGC, which becomes more mobile at neutral and alkaline pH values.

The physical differences between mine waste and top-dressing provide an interface that is vulnerable to fluvial erosion processes. To mitigate against the loss of topdressings or topsoil by run-off, physical erosion control measures constructed from natural materials may be introduced (Section 5.5.4). For larger open areas (e.g. 7a and 9 in Figure 6-7), the formation of smaller compartments may be necessary, for example by creating a grid pattern with interlocking branches of gorse cut from nearby land, or by positioning low-profile woven willow hurdles or coir rolls among stone rows. For smaller and narrower sections, encircling with suitable materials may suffice to keep the top-dressing in place.

Run-off from higher ground onto newly established phytostabilisation areas should be minimised. This can be achieved by deflecting drainage away from the areas using natural materials, such as coir rolls among stone rows, as discussed in Section 5.5.4.2. This is particularly indicated around the main MSD (7a in Figure 6-7). The southern edge is already protected by a stone wall that separates the area below the calciner row from the MSD, while drainage from the flat tailings surface of MSD should be prevented from running off the slope break and onto the underlying sandy mine spoil on the MSD slopes 7b&c (Figure 6-7). Run-off from MSD should also be managed along the southern edge of WT to protect phytostabilisation measures in area 9.

Less intense phytostabilisation measures can be applied to the large areas of wastes and tailings that are partially vegetated (areas 2, 3, 4, 5, 7b, 8, 10 and 11a&b in Figure 6-7). Soil amendments for coarsely and finely grained substrates, respectively, may be mixed with harvested seeds and applied among the existing vegetation.

Annual legume plant seed (e.g. *Trifolium repens*) may be added to any of the soil amendments and seed mixtures to improve the soil nutrient status and add organic matter to condition the soil for the following season (Section 5.5.4.1).

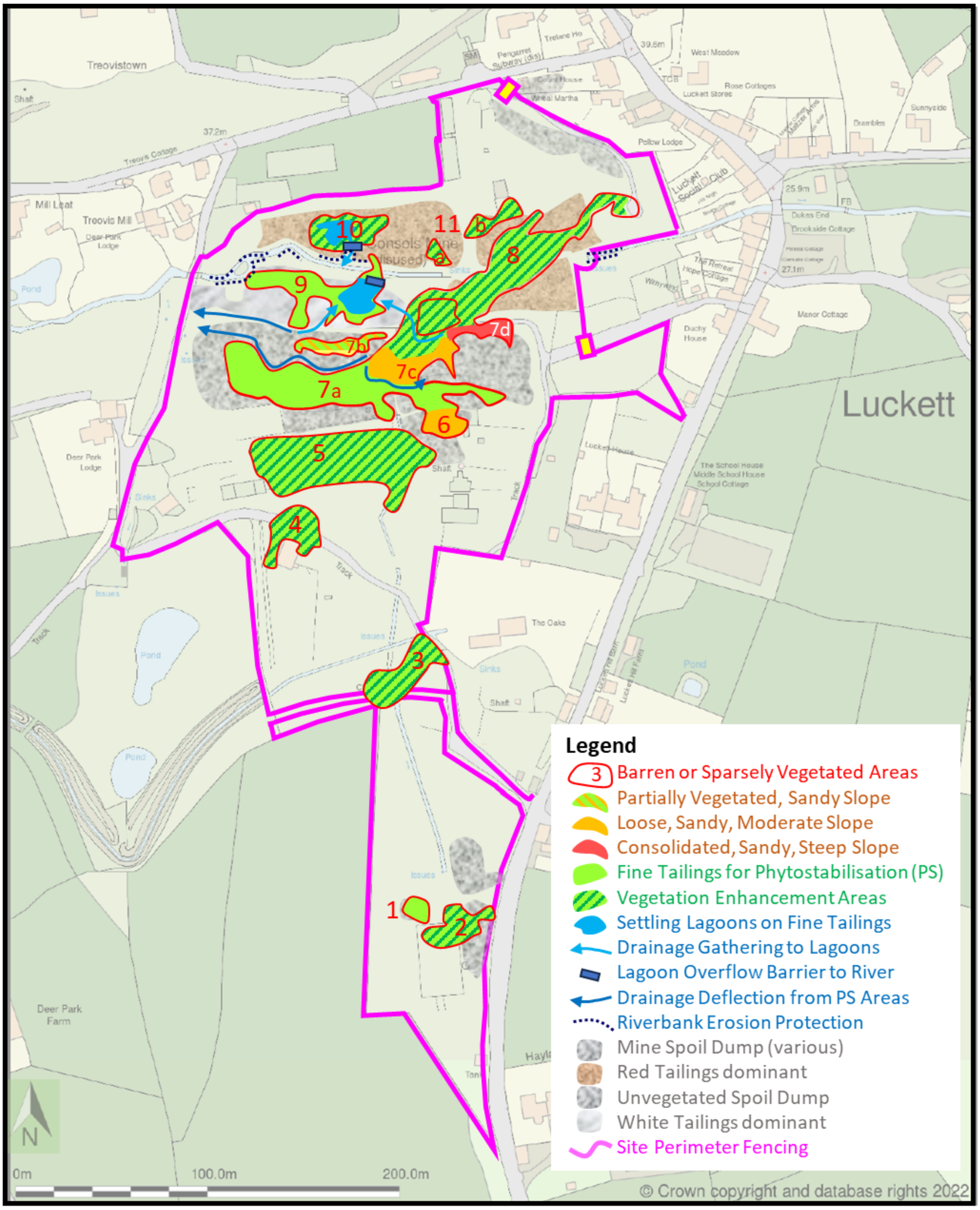

Figure 6-7 Map of phytostabilisation, run-off control and watercourse management options for NGC (see legend for details). Numbers are referred to in the text and in Table 6-1 and Table 6-2). Map base as for Figure 4-28. © Crown copyright and database rights 2023 Ordnance Survey 100049047.

Where vegetation density allows within the damp soils of woodland areas, the introduction of native poplar and willow species may be considered as means of additional hydrological control on the site.

6.6.3 Erosion Control on Partially Vegetated Slopes

The principles of phytoremediation also apply to slope stabilisation, with the complication that the retaining of topdressings and establishment of a plant community is more challenging (Section 5.5.4.1). The largest barren slope areas at NGC are the moderately steep, loose, sandy, north-facing slopes of the main MSD and USD (7c and 6, respectively, in Figure 6-6), and some apparently more consolidated, steeper slopes of coarsely grained material (7d). Either may be treated by:

i) positioning of hurdles and leaky dams woven from natural materials at the base of slopes (Figure 6-8),
ii) application of soil amendments for coarsely grained material mixed with locally sourced seeds of grasses, legume and gorse (see Section 6.6.2)
or hydroseeding incorporating biochar, mulch and binders with a grass/legume mix as described in Section 5.5.4.1,
iii) coverage of entire barren slope behind hurdles with interlocking spiny vegetation, such as gorse (Figure 6-8), whereby care should be taken to maintain adequate light levels for germination and growth,
iv) where necessary, deflection of drainage away from slopes and revegetation areas (see Figure 6-7), using natural materials, such as coir rolls among stone rows.

As an alternative to iii), loosely woven brush matting or coir erosion control blankets could be used, but these would have to be staked, which may disturb the ground, resulting in additional points for erosion to start.

The sourcing and preparation of natural materials used to implement erosion control and phytostabilisation areas may be an opportunity to involve the local population and schools in hands-on outreach activities that could form part of the public engagement and education package associated with the project.

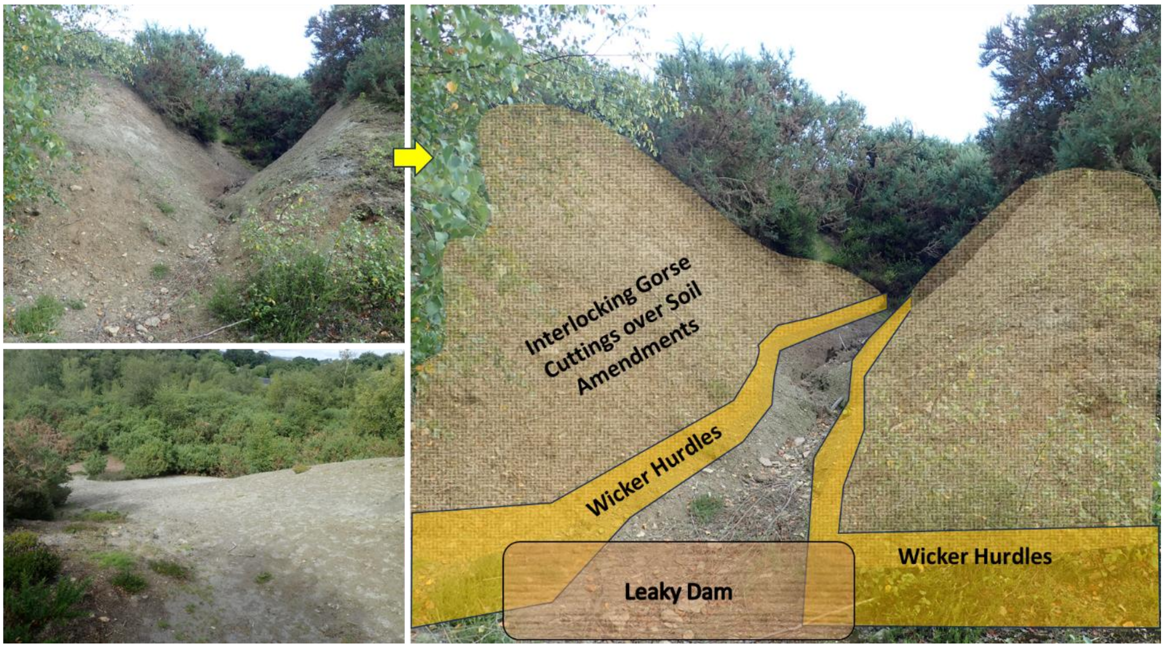

Figure 6-8 Erosion control at slopes using leaky dams and hurdles made from natural materials (willow, hazel) at the base of slopes and drainage points. Interlocking cuttings of brash wood from thorny vegetation, such as gorse, can be used to cover the slope from the base up to hold soil amendments in place. Top left and main image: steep slope 7d in Figure 6-7. Bottom left: moderately steep slope 6 in Figure 6-7.

6.6.4 Enhancement of Existing Settlement Lagoons on Tailings

On the fine-grained tailings in the river bottom, pooling of rainwater and run-off from mine waste has been observed after periods of moderate to heavy rainfall (Figure 4-7 and area marked blue within outlines 9 and 10 in Figure 6-7). Each features a preferential flow path to the river. Although it cannot be recommended to excavate the pools or generate scrapes elsewhere using machinery, the existing areas could be readily modified to construct a more effective settling pool for the entrapment of mine waste particles transported from higher to lower ground:

i) direction of flow from uphill mine wastes towards settling pond (area 9 only),
ii) strengthening and potentially raising of settling pond perimeters using natural materials, such as coir rolls among stone rows,
iii) emplacement of interlocking thorny vegetation cuttings in the vicinity of the overflow to slow the flow and aid settling of particles,
iv) slowing and potentially raising the overflow using natural materials, such as coir rolls and leaky dams strengthened with stone rows.

The overflow of the lagoon in area 10 is badly eroded and requires work akin to riverbank erosion control, discussed in the following section.

6.6.5 Erosion Control on Riverbanks

The banks of Luckett Stream are made up from mine tailings along its course through the site, with the possible exception of the culvert, which may provide some isolation from the waste. Under high flow condition, riverbank erosion occurs readily, as freshly exposed layers of tailings and undercuts show (Figure 3-3, Figure 4-8). Apart from the 'whole catchment approach' to natural flood management upstream of the site mentioned briefly in Section 6.6.1 and discussed in more detail in 5.5.4.3, erosion control measures within the NGC site require the positioning of strong and lasting materials to shore up and protect its banks from further erosion of contaminated material:

1) several bends are exposed to erosion and require shoring up with strong materials, such as flexible rock rolls at the toe of the mine waste to protect tailings from the full impact of the water velocity, especially at high flow,
2) behind and above the rock rolls, flexible natural materials, such as coir or straw rolls, brushwood fascines, brush matting or wattles, can be positioned to entrap sediment from the river as well as erosion products from above,
3) where possible, natural geotextile rolls or mats containing soils pre-seeded with calcifuge grasses may be placed at the top of the riverbank to encourage the establishment of vegetation over time.

Approximate locations of obvious need for riverbank erosion control are given in Figure 6-7. However, the exact locations of erosion control measures should be subject to further surveys on site.

6.7 Discussion and Limitations

The limitations of nature based solutions and green and sustainable remediation interventions (NBS/GSR) have been discussed in Section 5 and are predominantly related to their inherent characteristic of *not* aiming at the complete cessation of pollution. The intervention options presented here have been selected in the spirit of working with nature to reduce the export of contamination to Luckett Stream, which is the dominant aim of the project. In this respect, most measures seek to limit the physical erosion by wind, rain and footfall and to reduce the generation of acid mine drainage through water ingress into contaminated mine waste and shallow groundwater movement. Table 6-2 summarises the concerns, remediation approaches and their priorities with reference to Table 6-1, Figure 6-5 and Figure 6-7.

From a regulatory perspective, the main element of concern in Luckett Stream is copper. In this context several caveats with respect to the efficacy of the remediation measures should be noted:

1) The NBS/GSR interventions for NGC do not specifically target copper but seek to reduce the export of the whole suite of contaminants from the site into the wider environment, including the river. For example, the immobilisation of copper by soil amendments that raise the pH are not recommended, as they would aid the mobilisation and export of arsenic compounds.
2) The deep below-ground hydrology of NGC remains unknown and any reduction of underground sources and pathways of copper and other metal/loids into the hyporheic zone of the stream are beyond the scope of this project (Section 4.5).
3) The catchment upstream of NGC contains significant sources of copper that are beyond the control of this project (Sections 4.6 and 4.7).

The efficacy of interventions on water and sediment quality, suspended particulate load and erosion intensity should be evaluated over time to provide data that converts this project into a pilot for NBS/GSR applications elsewhere. For this, a carefully designed monitoring programme should be developed, potentially in collaboration with partner organisations that provide added educational services, such as the University of Plymouth.

Table 6-2 Summary table of intervention options for the remediation of concerns at New Great Consols mine site. The colour coding refers to the priority of intervention measures, from low to medium and high in green, purple and red, respectively. The effort column is an indication of projected resource intensity in terms of time, cost and/or external engagement. The numbers refer to areas as labelled in Figure 6-7.

Area	Concern	Interventions	Effort
NGC	public access, erosion through footfall	discouragement of access through secure perimeter fencing and/or planting of impenetrable vegetation; public engagement	high
Trail	access to extreme contamination	denial of access through secure fencing of Kit Hill Link Walk through the site	high
(1)	high contamination	discouragement of access through secure fencing and/or planting of impenetrable vegetation; phytostabilisation of fine tailings	high moderate
(2)	moderate contamination	enhancement of existing vegetation cover through phytostabilisation of coarse mine waste and stony slopes	low
(3)	high contamination	enhancement of existing vegetation cover through phytostabilisation of finely grained mine waste	moderate
(4)	high contamination	enhancement of existing vegetation cover through phytostabilisation of finely grained mine waste	moderate
(5)	public access, unsafe structures, extreme contamination	denial of access through secure fencing; prevention of water ingress to calciners by construction of shelter; phytoremediation through planting wind breaks and hydraulic control plants; enhancement of existing vegetation cover through phytostabilisation of fine tailings	high high moderate low

(Table 6-2 continued on next page)

(Table 6-2 continued)

Area	Concern	Interventions	Effort
(6)	moderate contamination	reduction of physical erosion and leachate generation through phytostabilisation of coarse mine waste slope	moderate
(7)	high contamination	reduction of erosion and leachate generation through phytostabilisation of fine tailings (7a) and coarse mine waste slopes (7b,c&d); run-off control	moderate moderate low
(8)	moderate contamination	enhancement of existing vegetation cover through phytostabilisation of fine tailings; phytostabilisation of bare, compacted tracks on fine tailings	low moderate
(9)	high contamination	reduction of run-off and leachate through phytostabilisation of bare, compacted fine tailings; enhancement of water pooling area into settlement lagoon and run-off control	moderate moderate
(10)	high contamination	enhancement of existing vegetation cover through phytostabilisation of fine tailings; enhancement of water pooling area into settlement lagoon and run-off control	low moderate
(11)	moderate contamination	enhancement of existing vegetation cover through phytostabilisation of fine tailings	low
River	erosion of tailings	water course management through whole catchment approach for Luckett Stream; planting for hydraulic control outside NGC perimeters; reduction of tailings erosion through shoring up and revegetating riverbank within NGC	high high high
Public	community	engagement of local population with the project from outset; public information and education through display boards, interactive website, guided tours	moderate high

7 Glossary

Abiotic Oxidation – oxidation process not involving biological activity by microbes, such as bacteria.

Acid Mine Drainage (AMD) – acidic and metal-rich discharges from adits and leachate of mine waste dumps that are the result of oxidation of sulfide ores where no acid neutralising capacity is present within the country rock (e.g. siliceous sedimentary and igneous rocks with no or only minor carbonates present).
AMD is the result of the oxidation of sulfide minerals in mines, waste dumps and tailings. Minerals deposited by intrusive processes, such as led to the generation of the granite batholiths in the Southwest, have been formed as sulfides under the exclusion of oxygen (e.g. pyrite, chalcopyrite, sphalerite, arsenopyrite, galena). Upon chemical and biologically mediated oxidation, these minerals release acid, dissolved metals and sulfate, which may be leached by water ingress and transported into the wider environment. The chemical reactions involved are exemplified with pyrite (FeS_2) here:

1) $FeS_{2\,(s)} + H_2O + {}^{7}/_{2}O_2 \leftrightarrows Fe^{2+} + 2SO_4^{2-} + 2H^+$
2) $Fe^{2+} + ¼O_2 + H^+ \leftrightarrows Fe^{3+} + ½H_2O$
3) $Fe^{3+} + 3H_2O \leftrightarrows Fe(OH)_{3\,(s)} + 3H^+$
4) $Fe^{3+} + 2½\,H_2O + ¼O_2 \leftrightarrows Fe(OH)_{3\,(s)} + 2H^+$

and, at low pH values (pH < 3.5):

5) $FeS_{2\,(s)} + 8H_2O + 14Fe^{3+} \leftrightarrows 15Fe^{2+} + 2SO_4^{2-} + 16H^+$

The oxidation of pyrite (1) occurs abiotically or by direct microbial oxidation. Reaction (4) is predominantly abiotic at pH >4.5 and slows down as the pH decreases. Below pH 4.5 the rate of this process is determined by microbial activity. At lower pH values, reaction (2) is solely dependent on microbial oxidation, and its rate determines the rate of the chemical reaction (5). The processes described in equations (1) and (3) to (5) contribute to the progressive release of protons, and hence lowering of pH [104-106].

Adit – a tunnel or passageway into an underground mine, usually nearly horizontal, through which the mine is drained of water, ventilated or accessed.

Aeolian Transport – lifting and entrainment of particles from a solid surface with air movement (wind)

Aqua Regia – a combination of nitric acid and hydrochloric acid in a molar ratio of 1:3. It is commonly used for extracting inorganic elements (e.g. metals) from solids (e.g. sediments or soils) by means of dissolution of the matrix and target elements. Some minerals, such as quartz, are resistant to hot *Aqua Regia* digestion and for this reason, the term ‘pseudo-total’ extraction is sometimes used in relation to data obtained by hot *Aqua Regia* digestion.

Anion – negatively charged species of a chemical element or compound (e.g. sulfide, phosphate, carbonate).

Aragonite – carbonate mineral ($CaCO_3$) formed by chemical precipitation in shallow tropical waters.

Arsenopyrite – sulfide ore of arsenic containing iron (FeAsS), often also bearing cobalt (Co).

Batholith – large body of igneous rock that formed by the intrusion and solidification of magma beneath the Earth’s surface, typically composed of coarse-grained rocks, such as granite or granodiorite.

Buddle – typically a round well within which a metal ore slurry is applied to a central shallow cone, and ore is separated from gangue by means of gravity, aided by running water and sometimes a brush.

Biochar – light-weight, porous product of the pyrolysis of biomass applied to increase soil fertility through provision of a source of slow-release carbon, minerals, cation exchange capacity and porous structure.

Carbonate Rock – rock or mineral that contains the carbonate ion (CO_3^{2-}) and cations, for example calcium (Ca: calcium carbonate and aragonite have the chemical formula $CaCO_3$ but different crystal structures).

Carbon Sequestration – in the context of phytoremediation, the uptake and storage of carbon in standing biomass and/or products manufactured from it, can be an added benefit.

Calcifuge – plants that prefer acidic soil.

Calciner – a furnace in which ores were roasted to drive off impurities, such as sulfur or arsenic from metal ore, such as tin. In the case of arsenic calcination, the sublimation of arsenic from arsenopyrite was followed by condensation of arsenic trioxide in a labyrinth.

Cation – an ion with a positive charge, such as metal ions (e.g. Fe^{2+}, Fe^{3+}, Cu^{2+}, Zn^{2+}).

Cerussite – carbonate ore containing lead ($PbCO_3$).

Chalcopyrite – sulfide ore of copper containing iron ($CuFeS_2$).

Chelation – simplified: the complexation of a metal by several ligands in a strongly bound formation (chelate complex) that is difficult to break.

Complexation – simplified: the binding of a metal or ion by a non-metallic molecule (ligand); ligands can be used to bind and extract metals from soils.

Country Rock – rock native to the locality.

DEFRA – Department for Environment, Food and Rural Affairs, a United Kingdom government department.

Diatomite – also referred to as diatomaceous earth, is the finely ground powder of celite, a siliceous sedimentary rock that consists of the fossilised remains of diatoms (algae); highly porous and promoting coagulation, it can be used as soil amendment in phytoremediation.

Efflorescent Salt – the migration of a mineral-rich solution (brine) to the surface of a porous material, where it forms a salt deposit when the water in the brine evaporates. In ore processing facilities, such as calciners, mortar and bricks are impregnated with minerals from fumes, which result in the formation of efflorescent salts during seasonal wetting-drying cycles.

Engine House – a building for the purpose of housing a (steam) engine on a mine site used for dewatering a mine, lifting or crushing ore.

Evapotranspiration – a combination of physical and biological processes by which water moves from the earth's surface into the atmosphere; comprises of the evaporation of water from surfaces, such as soils, water and plants, as well as the evaporation occurring through the openings (stomata) in the surface of plant leaves.

Exudate – fluid substance leaching from pores at the surface of organisms, such as skin, roots, membranes of bacteria etc. and includes saps, gums, resins, extracellular polymeric substances, chelates, etc.

Flue – a masonry-constructed conduit that connects a furnace or calciner to a chimney.

Fluorapatite – phosphate mineral containing calcium and fluorite ($Ca_5(PO_4)_3F$), a variation thereof is carbonate-rich fluorapatite ($Ca_5(PO_4,CO_3)_3F$).

Galena – sulfide ore of lead (PbS).

Gangue – economically worthless rock in which ore minerals are emplaced, overburden.

Guest Mineral – mineral or ore present in a mine that is, at the time of working, not of interest or economically viable to extract and process.

Hyperaccumulator – metallophyte plants that absorbs metal/loids through their root system and subsequently translocate them into their shoots, where they are accumulate at concentrations 100 to 1000 times higher than in plants of similar species or populations; used in phytoremediation.

Hyporheic Zone is the area of sediment or ground alongside and beneath the bed of a stream, where shallow groundwater (and potentially deeper groundwater) are mixing with the surface water of the stream and become part of the stream flow.

Igneous Rock – rock that forms through the cooling and solidification of lava (magma that has reached the surface as a result of volcanic activity, extrusive rock, e.g. basalt) or magma below the surface (intrusive rock, e.g. granite, gabbro, diorite).

Leaching – in the context of mobilisation of elements in nature, leaching is the process of a soluble element becoming extracted or detached from a solid by means of dissolution (e.g. of an ore) or desorption from a particle, followed by the transport away from the original substrate with the solvent, which in nature usually is water.

Labyrinth – a series of interconnected chambers constructed from masonry on whose walls arsenic was condensed from the flue gasses emanating from the connected arsenic calciner. Arsenic trioxide crystals were subsequently scraped off the walls and collected for further processing or sale.

Malachite – secondary copper mineral containing carbonate and hydroxides ($Cu_2(CO_3)(OH)_2$).

Metallophyte – a plant that tolerates high concentrations of metals (or metalloids) in soils by employing a range of strategies for detoxification.

Metamorphism – mineralogical and structural changes in solid rocks as a result of physical and chemical conditions that are different from those under which the rocks were originally formed (e.g. temperature, pressure, fluids).

Metamorphic Aureole – zone of contact metamorphism of the country rock in the vicinity of hot intrusive igneous bodies.

Mine Waste – also referred to as 'mineral working deposit' in the Town and Country Planning Act 1990; 'any deposit of material remaining after minerals have been extracted from land or otherwise deriving from the carrying out of operations for the winning and working of minerals, in on or under the land' [107].

Microbiome – in the context of soils, it encompasses microorganisms, fungi and some algae that affect soil structure and fertility.

Microorganisms – microscopic organism existing as single cell or in colonies of cells; includes bacteria, archaea, protists and protozoans.

Mine Spoil – generic term for the mine waste generated by the extraction of earth resources, such as coal, metals, precious stones; contains inert country rock, rubble and is contaminated by guest minerals and residual ore minerals.

Montmorillonite – micro-crystalline aluminosilicate clay that can be used to increase the water retention of soil.

Nature-based Solutions (NbS) – defined as 'working with nature, not against it', also as actions that (i) are inspired by or supported by or copied from nature, (ii) enhance the resilience of ecosystems, (iii) are resource efficient and are aligned with aims of social, environmental and economic sustainability. NbS has been adopted by the European Union as strategy for achieving, among other aims, the restoration of degraded ecosystems and climate change adaptation and mitigation [https://www.mdpi.com/2071-1050/12/8/3305].

Oxianion – a negatively charged ionic compound between an oxygen atom and another chemical element; environmentally important oxyanions include carbonate, phosphate, nitrate, sulfate and arsenate.

Oxidation – a chemical process that involves the loss of electrons from an atom; it causes the change in the oxidation state of elements. Metals lose electrons to gain a more stable electron configuration and form (more) positively charged ions (e.g. Fe^{2+} is oxidised to Fe^{3+} in the AMD formation reactions above; neutral/native iron (Fe) becomes the positively charged ion Fe^{3+} when it rusts). Oxidation also occurs in nature, with photosynthesis and composting organic material being two examples. Many oxidation processes in nature involve the activity of bacteria, fungi and other microbes.

Physico-chemical characteristics – important physical and chemical parameters that influence the geochemical and biogeochemical processes occurring in an environmental matrix, such as water, groundwater, soil, sediment, mine waste etc.; they include pH value, redox potential, ionic strength, temperature, moisture content.

Pyrolysis – thermal treatment of organic matter (biomass) under oxygen-limited conditions resulting in thermochemical conversion into a product, such as charcoal or biochar.

Red Mud – industrial waste product resulting from the processing of bauxite (aluminium mineral) into aluminium; also called bauxite tailings, contains various oxides, including iron oxides and has very high alkalinity (pH > 12).

Redox Potential – is a measure of the tendency of a chemical species to lose to or gain electrons in a reaction; in practical terms the redox potential provides information on the mobility and reactivity of metal/loids and compounds in the environment.

pH – is the negative logarithm of the hydrogen ion activity in a solution; in practical terms, it provides a measure for the alkalinity or acidity of a solution and can be used to predict the mobility and reactivity of metal/loids and compounds in the environment.

Saltation – is a type of particle transport by air movement, whereby loose particles are removed from a solid surface and leap or jump a distance before returning to the solid; important in aeolian transport of soils, desert sand, snow drifts where wind velocity is not strong enough to entrain and maintain particles in suspension over longer distances.

Shaking Table – table at a shallow angle that features a set of rills; ore slurry is applied to the top end and separated from the gangue by means of gravitation, water flow and vibration.

Siderite – carbonate ore of iron ($FeCO_3$).

Sorption – physical and chemical processes by which one substance becomes attached to another; examples include the adsorption of metal ions onto solid surfaces (cation exchange).

Sphalerite – sulfide ore of zinc (ZnS), often also bearing cadmium (Cd).

Substrate – in the context of this report, a layer in the environment, such as soil, mine spoil, sediment, on and within which organisms live.

Sulfide Ore – class of minerals characterised by the linkage of a sulfur anion (S^{2-} or S_2^{2-}) to a metal or metalloid (semimetal).

Phosphate Mineral – class of minerals containing the phosphate anion (PO_4^{3-}).

Pyrite – sulfide ore of iron (FeS_2).

Tailings – waste produced from separation processes used to recover economic minerals, comprising a slurry of fine rock (gangue) and remaining ores deposited in lagoons that dewater and compact over time.

Varsican Orogeny – geological mountain-building event caused by Late Palaeozoic continental collision.

Zeolites – are crystalline aluminosilicates with highly porous structure that are used in industry as adsorbents and catalysts.

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9 Appendix: Notes in Support of Risk Assessment for Works on Site

New Great Consols is a legacy mine site that benefits from some potentially hazardous structures having been made safe, including the fencing of engine houses, shafts and adit portals. Nevertheless, the surveys undertaken for this report identified some issues that should be carefully considered when carrying out Risk Assessments for remediation works (Section 6) being undertaken on the site. These include:

- potential toxicity of efflorescent salts on structures (Sections 3.4, 4.4 and 6.3),
- concentrations and potential toxicity of mine waste with respect to dermal exposure, ingestion or inhalation (Sections 3.7.1 and 4.4),
- contact with water, with respect to general contamination (pathogens) arising in the whole of the catchment, and mining-related contamination (Section 4.7),
- working near fast-flowing river with steep banks and culvert (Figure 4-10),
- working on uneven ground, on unstable slopes covered in lose material, near potentially unstable legacy buildings and the potential to encounter steep drops and/or unsecured shafts (Section 6.3).

This list represents the main points observed during the process of preparing this report and does not claim to be exhaustive or complete.

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