Surface water management and encapsulation of mine waste to reduce water pollution from Frongoch Mine, Mid Wales

Paul Edwards, Tom Williams, Peter Stanley

Natural Resources Wales (NRW), Cardiff, CF24 0TP, Wales, United Kingdom, paul.edwards@naturalresourceswales.gov.uk, tom.williams@naturalresourceswales.gov.uk, peter.stanley@naturalresourceswales.gov.uk

Abstract

Abandoned metal mines are the principal cause of failure to achieve Water Framework Directive (WFD) standards in Wales, with 1,300 mines impacting over 100km of rivers. Frongoch was one of Wales' most productive lead mines during the 18th and 19th centuries, consequently becoming one of our most polluting abandoned mines. NRW received financial support from the European Regional Development Fund (ERDF) via the Welsh Government (WG) to implement a remediation scheme and reduce impacts.

A stream was diverted in 2011 to prevent it flowing into mine workings that discharge via Frongoch Adit, reducing its metal load. A perimeter channel was created in 2013 to direct surface water away from spoil towards a new flood attenuation pond. Three hectares of mine waste were re-profiled and capped in 2015 to minimise water ingress and to convey clean runoff via drainage channels into a series of ponds, creating a new wetland habitat. Wide consultation at design stages ensured the remediation didn't adversely affect the mine's unique features or statutory designations. NRW engaged ecologists to enhance biodiversity and archaeologists to supervise construction.

Although further monitoring is required, this project demonstrates how water quality improvements can be achieved with low ongoing maintenance, whilst providing local biodiversity and landscape benefits. The scheme will not achieve compliance with WFD in all recipient watercourses, but virtually all water from the mine is now controlled via one surface water and two groundwater discharges, one of which has reduced in volume by 80%. These discharges have flow gauging weirs, providing opportunity for ongoing research and development for institutions, innovators and regulators. This paper discusses the scheme, its achievements and opportunities going forward.

Key words: Metal mine remediation, Water Framework Directive, lead, zinc, cadmium

Introduction & historical background

Frongoch Mine is situated in a rural setting near the village of Pont-rhyd-y-groes, ~245m above ordnance datum (AOD), 17km south east of Aberystwyth. It was one of Wales' most productive lead mines during the mining renaissance of the 18th and 19th centuries, producing 58K and 50K tons of lead and zinc ore respectively (Bick 1996). Prior to remediation, Frongoch was ranked as Wales' second most polluting mine (Mullinger 2004), annually discharging 23 and 1.5 tonnes of zinc and lead.

Mineral ownership at Frongoch belonged to the Earls of Lisburne and mineral rights changed to the west of the watershed, where the same lode was mined at Wemyss Mine (Fig.1). A lease of 1759 is recorded, though Frongoch remained a small mine until 1790, when new management invested. The mine operated initially as Bron-y-Goch and Llwynwnwch mines, but the most successful period was 1834 to 1874, when the two leases were consolidated (Bick 1996).

The capacity of upstream reservoirs was increased to improve seasonal availability and a steam engine introduced ~1842 to aid dewatering (Bick 1996). The Wemyss mine was acquired around this time and its adit was extended to connect with the Frongoch 24 fathom level. In all, thirteen levels were driven, generally at 22m intervals. Shafts terminated at varying levels, the deepest at ~282m (Jones 1922).

The French mining engineer Moissenet visited in 1860 to record the industrial processing and found that even though four vast reservoirs were used, water was scarce at surface and recycled for hydropower at the large 60hp waterwheel at Wemyss Pumping Station. Moissenet recorded the processing from north to south with stamp, crusher and winding houses, jigging tables, gravity separation using water and round buddles, the Lisburne buddle and Zenner rotating table (Bick 1996).

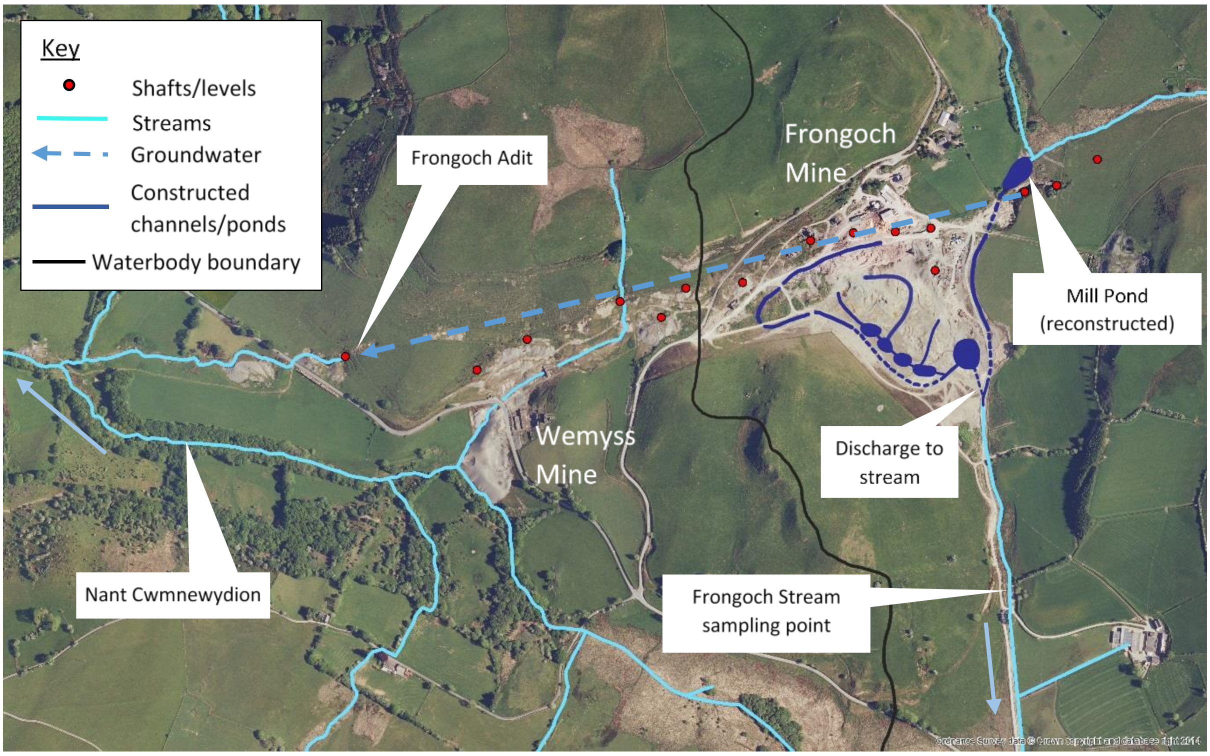

***Figure 1** Aerial photo of Frongoch and Wemyss mines in 2009 showing surface and groundwater pathways, including channels and ponds constructed from 2011 to 2015.*

Although the galvanising process was UK patented in 1837, reportedly only lead was mined from 1859 to 1876 with sphalerite production generally avoided due to low commodity prices. Much sphalerite was therefore perceived to have passed to the spoil heaps. Although the mine had flourished with proven reserves at depth, it became unprofitable due to coal import costs and hard ground at depth. A new owner extended Vaughan's Shaft to ~282m, but found the vein too hard to exploit, so from 1879 began stripping the walls of remaining mineralisation and removing *in situ* supporting pillars (Jones 1922).

The Belgian Société Anonyme Minière modernised the mining in 1898, adopting electricity generated from the Pont Ceunant hydro-electric scheme (Bick 1996). The onsite ~1.2ha reservoir used for operating the Wemyss wheel became redundant and was probably adopted as a tailings lagoon, either on introducing hydro-electricity or when mining ceased and the dressing mill was used for reworking the dumps in 1903. The venture collapsed in 1904 (Jones 1922).

Final large-scale working of mine spoil dumps occurred in the 1920s when sorted mine spoil was transported ~2.8km by aerial ropeway to the Gwaith-Goch dressing mill in the Ystwyth valley (Bick 1996). An option of extending the Grogwynion deep adit, also in the Ystwyth valley, by driving it a further ~1.3km north and draining Frongoch to a level of ~139m was not pursued (Jones 1922).

Geology, hydrology & geochemistry

Frongoch is situated on the Devils Bridge Formation in the Early Telychian Stage of the Silurian Period. It is a thick basin "slope apron" sequence of thinly interbedded mudstone and sandstone turbidite couplets, and is quoted as being over 900m thick. The Frongoch Borehole drilled onsite confirmed the sequence to be over 250m in thickness. The strata in the Central Wales Orefield has been widely faulted by two fault sets. One trends NNE-SSW along anticline and syncline structures that bear little mineralisation, whereas the second, like the Frongoch Fault, has cross cutting faults that strike broadly ENE-WSW and are near vertical and mineralised. The faults subject to high pressure fluids resulted in rounded breccia and gangue hosted ore-rich veins from less than 1m to 30m thick (British Geological Survey 1997).

The mine was worked for a length of ~1.5km and the vein reported as consistently 11m thick. The greatest yield was a 220m section by Vaughan's Shaft where the galena ore was 3.6m to 7.2m wide (Jones 1922). The vein contained two separate galena rich lodes and a sphalerite lode on the footwall. The metal lodes were perceived to taper with depth along strike, but were consistent in width; the south galena lode 1.8m wide and north galena lode 6.4m at 260m level in Vaughan's Shaft (Jones 1922).

Several thousand tonnes of mineral dumps were moved to the east of the site in 2003 and bear world class Pb-Zn-Cu supergene minerals formed over three stages. Consequently, this site was designated as the Mwyngloddfa Frongoch Site of Special Scientific Interest (SSSI). The earliest Tertiary supergene stage is represented by large pyromorphite and cerussite crystals and the rarer second stage formed during post glacial weathering is represented by the same microcrystalline species plus wolframite. The post mining stage yields bechererite, caledonite and susannite plus rare lead bearing species corkite and hinsdalite often found in oxidised zones of polymetallic sulphide deposits (Cotterell & Todhunter 2007).

Soils are generally thin and the upland terrain offsite lends itself to deep, shallow or modified peat horizons and glacial till on topographic lows with onlapping soliflucted head deposits with varying gravel content on the slopes (Palumbo-Roe *et al.* 2012). Superficial deposits onsite include coarse spoil, coarse sand graded mine spoil and, in the former reservoir, fine sandy silt-clay tailings.

Rainfall upstream on the Ystwyth is ~2000mm/yr. Drainage at Frongoch is governed in the west by the Nant (Stream) Cwmnewydion, which drains to the Afon (River) Magwr and Afon Ystwyth, and in the east by Frongoch Stream, which joins the Nant Cell and thence the Afon Ystwyth upstream at Pont-rhyd-y-groes. A number of large reservoirs were constructed to support mining, including Pond Rhosrydd and Pond Glandwgan to the north west, while Llyn Frongoch and Llyn Llwynwnwch supplied water to Mill Pond from the north east. The onsite ~1.2ha reservoir fed the Wemyss pumping house.

The hydrology and hydrogeology was substantially changed by ore extraction and development of open workings between Llwynwnwch and Edward's shafts at the north east of the site. Modification of drainage had enabled surface water from Mill Pond to cascade directly into open workings, flowing along the worked lode and discharging at the Frongoch Adit portal (~185m AOD) (Fig.1). Surface water runoff is from north to south across the mineral processing area towards the tailings lagoon and Frongoch Stream; during storm events this was considerable and eroded fines. A culvert discharges to Frongoch Stream (~231m AOD) and yields a seasonal discharge that originates from the dressing floor direction.

The Conceptual Site Model has developed particularly around the fine-rich tailings lagoon. Trial pits along this lagoon confirmed 0.6-1.15m of heterogeneous silty clays, frequently finely laminated and sandy (fine), becoming sand and peaty at the base laying upon ~1.2m or more peat and 1m of silty clay on slate gravel (Palumbo-Roe *et al.* 2009). Electrical resistivity tomography and ground penetrating radar indicated the upper silty clay (~1.2m) to be the lagoon base with a more conductive zone extending well below (Kuras *et al.* 2011). Later excavations corroborated a highly fractured bedrock with overlying clay rich till and isolated, generally beneath the lagoon, peat horizons (Palumbo-Roe *et al.* 2012). Outside the lagoon footprint, gravel to coarse sand mining waste and cobbles extended laterally.

Gravel in head deposits on surrounding hills conveyed drainage towards the site onto till deposits allowing some recharge of tailings. Perched groundwater was identified in a remnant launder, on the lagoon base, but also on till. The implied groundwater pollution of the fractured bedrock was subsequently confirmed as an attenuating plume (Bearcock *et al.* 2010).

Groundwater flows rise in the mine workings via an old stope (~190m AOD) to 24 fathom level near the watershed and thence drain via Frongoch Adit (Palumbo-Roe *et al.* 2012). The culvert into Frongoch Stream is also capable of draining the tailings and/or the glacial till, and lead concentrations increased in a tailings borehole in winter, implying seasonal flushing of lead precipitates (Bearcock *et al.* 2010).

ICP-AES analysis yielded relatively low concentrations in the shallow samples and those beneath the tailings lagoon base. Lead was between 1-40g/kg, but enriched up to 127g/kg at 1.4-1.65m in finely laminated clays, which were the most leachable in sequential extraction. Zinc ranged from 40-112g/kg throughout the unweathered tailings profile and cadmium from 0.05-0.4g/kg (Palumbo-Roe *et al.* 2009).

Chemometric data processing (CISED) did not reveal carbonate components, but revealed sulphates in near surface and sulphides or oxyhydrides at the lagoon base and beneath. Galena was present from 0.74m and enriched (~10%) at 1.4-1.65m and anglesite [$PbSO_4$] traces detected from 0.74-1.4m. Surface bianchite [$(Zn,Fe)SO_4 6H_2O$] efflorescence was observed during a dry summer with an appreciable amount of zinc recorded in deionised water extraction. This is indicative of deeper sulphide weathering, upward capillary transport and sulphate precipitation in the shallower unsaturated zone, which is more readily soluble during wet dry seasonal cycling (Palumbo-Roe *et al.* 2009).

Environmental impacts

Based on the 2015 classification, all of the watercourses downstream of Frongoch Mine are failing to achieve the environmental quality standards required by the WFD, mainly due to elevated concentrations of zinc. Frongoch Mine is the primary cause of the zinc failures in Frongoch Stream, Nant Cell, Nant Cwmnewydion and Afon Magwr. It is also one of the two major sources of zinc in Afon Ystwyth, the other being Cwmystwyth Mine (Stokes 2012).

Fish population surveys carried out by Environment Agency Wales (EAW) in 2009 confirmed Nant Cwmnewydion was virtually fishless until its confluence with Afon Magwr, approximately 3.5km downstream of Frongoch Adit. Fish were also absent in Frongoch Stream and in Nant Cell downstream of its confluence with Frongoch Stream (2km downstream of Frongoch Mine) when they were surveyed in 2013. The invertebrate fauna was impoverished downstream of inputs from Frongoch Mine in both Frongoch Stream and Nant Cwmnewydion in 2009, with the number of taxa increasing with distance from source (Keenan 2015).

Remedial options appraisal

In February 2011, EAW (funded by WG) diverted Frongoch Stream to stop it overflowing from Mill Pond into an open stope at the north east of the mine, as recommended by Atkins (2010). The stream was diverted back into its original watercourse via a 450mm culvert from Mill Pond, leading to a concrete cloth lined channel on the eastern perimeter of the site, which remains relatively clean upstream of runoff and groundwater inputs from the mine.

An assessment of options for reducing the metals load to Frongoch Stream from the tailings dumps at Frongoch Mine was undertaken (Atkins 2011). Four options were considered, ranging from re-profiling of mine spoil (do minimum) to re-profiling and capping mine spoil and providing vegetation and runoff treatment (most expensive). The overall aim was to reduce the volume of water entering the contaminated mine waste from direct infiltration of rainwater or from runoff entering the site from surrounding hillsides, thus reducing the opportunity for metals to be mobilised.

A grant of £690K from ERDF was matched by £460K from NRW for a project from January 2013 to June 2015. The total funding was less than the indicative cost for the most expensive option, so the design needed to be scaled to the available budget, with minimal ongoing maintenance costs.

Implementation of the preferred option

Atkins proposed construction in two phases to allow works that didn't require planning permission to be progressed under EAW's permitted development rights, while planning permission was obtained from Ceredigion County Council (CCC) for the remaining works. The phasing of the project also allowed experience obtained from Phase 1 to be incorporated into Phase 2.

Phase 1 was carried out by EAW between January and May 2013. A drainage channel was constructed along the northern and western perimeters of the site to intercept clean surface water and reduce the amount reaching mine waste. The channels were not lined as it was hoped the natural soils would be low permeability, however, the extent of the former tailings lagoon proved to be greater than expected, resulting in a portion of the perimeter channel passing through mine tailings. A pond lined with Geosynthetic Clay Liner (GCL) was built to receive flows from the perimeter channel and attenuate flows entering Frongoch Stream. The downstream flood risk was further reduced by the installation of a hydro-brake in the pond outfall, restricting the discharge to a maximum of 160l/s.

Following the completion of Phase 1, further geochemical assessment of the site was carried out in collaboration with Swansea University (Mustard 2013). Water quality data were collected during heavy rainfall events and a detailed characterisation of the different soil types across the site was completed with a portable X-ray fluorescence (pXRF) spectrometer. Soil samples were collected at key locations for laboratory 'wet analysis' and leachate testing. This study highlighted an area of particularly metal-rich material that roughly correlated with the area of the historical tailings lagoon and through which the Phase 1 channel flowed. The design of Phase 2 was modified to ensure priority was given to preventing surface water coming into contact with the most contaminated material.

Phase 2 was tendered and contractors were asked to quote for varying amounts of low permeability capping across the site to enable the works to be scaled to the available budget. A contract was awarded to include the full extent of proposed capping, with construction taking place between January and June 2015. Mine waste was excavated and deposited in the north of the site where it was re-profiled into a more regular landform to promote runoff. A series of cascading wetlands were created on the footprint of the former tailings lagoon in the south west of the site to encourage suspended solids to drop out of runoff and provide additional habitats for wildlife. These two areas were capped with a minimum of 300mm of locally sourced low permeability clay, with the wetlands and transfer channels also benefiting from the addition of a GCL below the clay. Drainage channels lined with GCL and low permeability clays were constructed to carry runoff into the wetlands. A section of pipe was placed in the Phase 1 perimeter channel to convey relatively clean water through the former tailings lagoon and under the new wetland area. The trench was backfilled with excavated fine tailings and capped. All capped areas were finished with 100mm of restoration soils, which included surplus capping material and naturally occurring site-won soils. This was seeded with a nurse crop of *Agrostis capillaris* (Common Bent) to establish fast vegetation cover, offering protection to the soils and stabilising slopes against erosion. Restoration soils in the drainage channels were afforded the additional protection of turf reinforcement matting.

In total over 23,000m^2 of the site was afforded a lower permeability cap during the Phase 2 works, and validation testing provided confidence that this was compacted sufficiently to attain the permeability requirement of 1x10^{-8}m/s. Topographical surveys confirmed an average clay thickness of 396mm, with over 450mm in some areas (up to 50% greater than required), which adds to the overall performance of the cap. The effect of the remediation on the landscape can be seen in Figures 2 and 3.

Constraints & mitigation

An environmental assessment was commissioned to assess likely impacts and set out measures to avoid or reduce negative impacts. The Environmental Report (Environment Agency 2012) was circulated to statutory consultees and other key environmental stakeholders for comments before finalising the designs for Phase 1. An updated version of this report (NRW 2013) was circulated for consultation before being sent to CCC with the planning application for Phase 2.

An initial scoping exercise identified potential environmental effects that could be screened out from further assessment due to their low impact. The remaining effects that were assessed included ecology, planning policy, recreation, public access, water resources, hydrology, soils, landscape and visual impact, cultural heritage and archaeology. An Environmental Action Plan was produced to outline the actions required to mitigate impacts of the works. Following mitigation, the majority of the permanent impacts were expected to be positive, including water resources, water quality and visual amenity. The only permanent negative impacts identified were cultural heritage and archaeology.

Frongoch Mine is within the Upland Ceredigion Landscape of Outstanding Historic Interest. Design development ensured that the unique historic features associated with the former mining operations were avoided, including the engine and crusher houses within the adjacent Scheduled Ancient Monument (SAM). The remediation changed the character of the mine, but the effect on landscape was predicted to be positive in the long-term as vegetation becomes established and naturalised. The most important ecological habitats on site are the lichen and bryophyte rich areas of Calaminarian grassland type. These areas were identified by surveys and their location was taken into account during the design of the earthworks. A number of stands of Japanese knotweed were present, which were avoided by the works where possible and managed by annual spraying. Habitats Regulations Assessment (HRA) screening concluded that there was no likely significant effect of the remediation on the Grogwynion Special Area of Conservation (SAC), approximately 6km downstream of Frongoch Mine.

Figure 2 *Photo of Frongoch Mine looking from north west to south east in October 2010.*

Figure 3 *Photo of Frongoch Mine looking from north west to south east in April 2016.*

A desk-study of the mine's industrial heritage, undertaken during the scoping exercise, divided the site into zones according to archaeological potential (Murphy 2012). This study informed the design of the remediation scheme, which avoided the SAM and a number of unscheduled building remains in the centre of the site. EAW excavated six archaeological trenches in August 2012, which were evaluated to identify buried remains across the site, create a deposit model clarifying the extent of overburden protecting these sites and identify areas in which structures were likely to be disturbed by the proposed works. Features of interest included the well-preserved remains of two buddle-pits, several wall-lines, tram rails, tramway banks, a reservoir bank and timber structures. The depth of these features varied from 0.2m to 1m below existing ground levels (Poucher 2012).

The archaeological evaluations demonstrated remarkable survival of structures depicted on historical maps, but also identified many features that were not on these maps, so an accurate plan of sensitive features couldn't be ascertained from these maps alone. A watching brief was therefore required during ground works in sensitive areas where the level of archaeological survival was unclear. The Phase 1 watching brief confirmed the presence of archaeological remains across the former mine site, but these were less frequent around the perimeter of the mine (Shobbrook 2013). Following Phase 1, open area excavations were pursued on a series of processing features that would be affected by the proposed Phase 2 works. The Phase 2 design was subsequently modified to avoid disturbing these features and to re-bury them. As a result of these design changes, few archaeological remains were recorded during the Phase 2 supervision (Murphy *et al.* 2015).

Monitoring & results

Results of fortnightly monitoring show an 80% reduction in flow from Frongoch Adit following the 2011 stream diversion (Table 1). Although metal concentrations in the residual flow increased, the zinc, lead and cadmium loads reduced by 44%, 63% and 58% respectively. The main benefit of this diversion was to increase dilution in the recipient Frongoch Stream, causing zinc, lead and cadmium concentrations to reduce by over 70%, while there was no observable change in metal concentrations in Nant Cwmnewydion downstream of Frongoch Adit.

Occasional metal concentration spikes were recorded in Frongoch Stream during construction and may be attributed to temporary disturbance of the former tailings lagoon. Since completion of the remediation scheme in July 2015, metal concentrations in runoff from the capped areas have been considerably lower than those observed prior to remediation, but other sources are still contributing to the metals load to Frongoch Stream. Most of these sources are now captured within the final discharge from the flood attenuation pond, including runoff from uncapped areas and a groundwater discharge discovered during the remediation. There is, however, a separate discharge to Frongoch Stream from an old drainage culvert, which hasn't reduced since the capping and has accounted for 47% of the observed zinc load in the stream post-remediation.

Local rainfall in the period from July 2015 to February 2016 was 50% higher than the long-term average; this will have influenced metal loads within this period. Therefore a longer period of post-scheme water quality and flow monitoring is required to fully evaluate the effectiveness of the remediation scheme. Additionally, stream sediment samples have been collected for analysis of metal concentrations, and monitoring of fish and invertebrate populations is planned for summer 2016.

Table 1 *Water quality and flow data from Frongoch Adit, the final discharge from the remediated site and from Frongoch Stream downstream of the final discharge (data from July 2004 to March 2016).*

Sampling location	Time period	Flow (l/s)	Total Zn (µg/l)	Total Pb (µg/l)	Total Cd (µg/l)	Zn load (kg/day)	Pb load (kg/day)	Cd load (kg/day)
Frongoch Adit	Pre-diversion	90	5,500	360	10	36	2.6	0.08
	Post-diversion	17	13,800	670	23	20	1.0	0.03
Final discharge	Pre-Phase 2	7	115,600	6,010	257	24	3.0	0.05
	Post-Phase 2	9	49,500	1,980	88	17	2.0	0.03
Frongoch Stream	Pre-diversion	17	13,300	1,220	27	18	1.4	0.03
	Post-diversion	65	3,600	270	8	22	2.0	0.05
	Post-remediation	89	2,900	200	6	28	2.1	0.05

Conclusions & future work

This project demonstrates how water quality improvements can be achieved with low ongoing maintenance, whilst accommodating statutory designations and providing local biodiversity and landscape benefits. Further monitoring is however required to fully evaluate the improvements with regard to WFD objectives. Residual groundwater discharges and areas of uncapped mine waste are still preventing achievement of water quality targets in the receiving watercourses, but a reduction in flow from Frongoch Adit and isolation of other groundwater sources should make future treatment more feasible and cost-effective. Virtually all water from Frongoch Mine is now controlled via one surface water and two groundwater discharges, all of which have flow gauging weirs that provide ongoing research and development opportunities for institutions, innovators and regulators.

Acknowledgements

The Frongoch Mine Remediation Project was partly funded by the ERDF, provided through WG and delivered by NRW with technical support from the Coal Authority. The scheme was designed by Atkins.

References

Atkins Ltd (2010) Frongoch & Wemyss metal mines – surface water control feasibility study. Atkins document ref. 5089842, June 2010.

Atkins Ltd (2011) Former tailings lagoon at Frongoch Mine – remediation options feasibility assessment report. Atkins document ref. 5098273, March 2011.

Bearcock J, Palumbo-Roe B, Banks V, Klinck B (2010) The Hydrochemistry of the Frongoch mine, mid Wales. British Geological Survey Open Report OR/10/006.

Bick D (1996) Frongoch Lead & Zinc Mine, British Mining No 30. A monograph of the Northern Mine Research Society, July 1996.

British Geological Survey (1997) Geology of the country around Llanilar and Rhayader.

Cotterell T, Todhunter P (2007) Corkite and Hinsdalite from Frongoch Mine, Devil's Bridge, Ceredigion, Wales, including evidence to suggest that Orpheite is a variety of Hinsdalite. Journal of the Russell Society, 10, 57-64.

Environment Agency (2012) Frongoch Metal Mine Remediation – Environmental Report. October 2012.

Jones OT (1922) Memoirs of the Geological Survey, Vol. XX, Lead and Zinc. The Mining District of North Cardiganshire and West Montgomeryshire.

Keenan E (2015) Investigation into the ecological status of watercourses downstream of Frongoch mine. Natural Resources Wales Technical Memo TMW15_11.

Kuras O, Banks V, Palumbo-Roe B, Klinck B (2011) Geophysical characterisation of a tailings lagoon at Frongoch Mine, Devil's Bridge, Ceredigion. British Geological Survey Open Report OR/11/005.

Mullinger N (2004) Review of Environmental and Ecological Impacts of Drainage from Abandoned Metal Mines in Wales. Environment Agency Wales report EATW/04/02.

Murphy F (2012) Frongoch Metal Mine Remediation Project – Archaeological Assessment. Dyfed Archaeological Trust Report No. 2012/11, Project Record No.102638.

Murphy F, Wilson H, Protheroe-Jones R (2015) Frongoch Metal Mine, Ceredigion – Archaeological Fieldwork 2014-2015. Dyfed Archaeological Trust Report No. 2015/30, June 2015.

Mustard G (2013) Geochemical characterisation and assessment of remediation works at Frongoch Metal Mine, West Wales. MSc dissertation, Swansea University.

NRW (2013) Frongoch Metal Mine Remediation (Phase 2) – Environmental Report. August 2013.

Palumbo-Roe B, Banks VJ, Bearcock J, Humpage AJ, Maurice L, Shaw RP (2012) Conceptual ground model update report for proposed remedial measures at the abandoned Frongoch Mine, Ceredigion, Wales. British Geological Survey Commercial Report CR/12/036.

Palumbo-Roe B, Klinck B, Banks V, Quigley S (2009) Prediction of the long term performance of abandoned lead zinc mine tailings in a Welsh catchment. Journal of Geochemical Exploration vol.100 pp169-181.

Poucher P (2012) Frongoch Metal Mine, Ceredigion, Archaeological Evaluation. Dyfed Archaeological Trust Report No. 2012/65. Project Record No. 103627.

Shobbrook A, Murphy F, Poucher P (2013) Frongoch Metal Mine, Phase 1, Ceredigion, Archaeological Watching Brief. Dyfed Archaeological Trust Report No. 2013/46. Project Record No. 105657.

Stokes, M (2012) WFD Investigation, Abandoned Mines Project, Afon Ystwyth. Environment Agency Wales Technical Report no. A&R_SW_12_06.