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Tracer test feasibility assessment: Frongoch Mine Tailings Lagoon

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Tracer test feasibility assessment: Frongoch Mine Tailings Lagoon

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Foreword

This report was commissioned by the Environment Agency to provide information in support of the design of a remediation scheme for Frongoch Mine near Devil's Bridge, Ceredigion, Wales. The report assesses the feasibility of tracer testing at the site to provide an improved understanding of the hydrogeology of an area of mine tailings.

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Summary

The feasibility of tracer testing at the Frongoch Mine site was investigated during a two day site visit. A walkover survey identified a potential tracer injection point where a surface stream sinks into tailings deposits. Water discharges through a culvert approximately 50 m from the sinking stream. The origin of the water in the culvert is unknown but it is thought to drain the tailings area. Tracer testing could be used to determine whether this is the case. A successful tracer test would demonstrate the travel times from the stream sink to the culvert, demonstrating whether there is a rapid preferential flowpath or whether groundwater flow occurs more slowly. Quantitative results (tracer mass balance and breakthrough curves) could be obtained from the Frongoch Stream gauging site.

Tracer testing using Sodium Fluorescein dye is not recommended at the Frongoch mine site due to loss of ~ 75% of the fluorescence, which is likely to be due to the presence of high concentrations of metals within the groundwaters. Bacteriophages are likely to be the best tracer at this location, and any tracer should be tested in groundwater samples from the site prior to a tracer test.

Single borehole dilution testing was carried out to assess the suitability of two boreholes as tracer injection points. Results indicated slow dilution times suggesting that tracer injected into these boreholes is unlikely to be detected at the culvert. Groundwater velocities were faster in the glacial deposits (~ 2–20 m/d) than in the tailings (~0.4 m/d), although there are no porosity data available for the glacial deposits therefore there is more uncertainty in the calculated groundwater velocity.

1 Introduction

On 6th and 7th February 2012 the Frongoch Mine Site was visited to assess the feasibility of carrying out a point to point tracer test to provide an improved understanding of the hydrogeology of the site. The feasibility assessment comprised: (1) A walkover survey to identify potential injection and monitoring sites; (2) Single borehole dilution tests in two boreholes to assess their suitability as tracer injection sites and determine groundwater velocities; (3) Background sampling to determine the suitability of fluorescent tracers in the groundwaters at the site. This report provides details of these activities and recommendations for how a tracer test could be carried out at the site.

2 Hydrological assessment of potential injection and monitoring points

2.1 GENERAL HYDROLOGY AND HYDROGEOLOGY

Surface water from Llyn Frongoch to the north of the Frongoch Mine site previously entered the Frongoch Stope to be discharged approximately 1.2 km to the west-south-west through the Frongoch Adit (Figure 2.1). A newly constructed lagoon prevents the surface water entering the Frongoch Stope, and the surface water is now diverted along the eastern perimeter of the Frongoch Mine site, emerging from a culvert to become the southwards flowing Frongoch Stream (Figure 2.2). Upstream of the Frongoch Mine site the surface water is unpolluted but as it passes the area of mine tailings the Frongoch Stream becomes contaminated with metals, in particular Fe, Al, Ni, Zn, Pb, Cd (Bearcock et al., 2010). It is understood that the main source of contamination is a small culvert that drains the area of mine tailings and enters the Frongoch Stream at point A on Figure 2.2. There is a gauging station on the Frongoch Stream downstream of the Frongoch Mine (point B on Figure 2.2), which EA staff reported had a flow of approximately 50 l/s at the time of the field visit. The flow in the culvert (point A on Figure 2.2, for picture see Figure 2.3) was not measured, but was estimated at ~ 3 l/s. The Frongoch stream flows along the eastern side of a road that also has a drainage channel running along its west side. At the time of the site visit a very small flow emerged into the base of this drainage channel at point C on Figure 2.2 and flowed slowly (less than 0.2 l/s) for a few metres before seeping back through the base of the drainage channel. The drainage channel was then dry until a second small spring that emerged over several metres and formed a channel of approximately 1–2 l/s that is culverted under the road at point D on Figure 2.2 and enters the Frongoch Stream.

The area of tailings continues approximately 100 m to the north of the extent shown in Figure 2.2. On 6th February there was a stream flowing from the northwestern edge of the area of tailings past boreholes 1 (F on Figure 2.2) and 3 (G on Figure 2.2) and across to a point on the southwestern side of the tailings where it could be clearly observed sinking into the ground (point E on Figure 2.2). The surface stream is pictured in Figure 2.4 with the sink points visible in Figure 2.5. The area of tailings contains several pools of water which may infiltrate slowly into the ground. At the time of the site visit there were many dry runnels and dry stream channels crossing the tailings that presumably flow during wetter periods. It is likely that some of this water infiltrates the ground as it crosses the tailings, perhaps through sinks similar to point E on Figure 2.2. However, some surface water is likely to recharge the tailings via ponds, and there appear to be many currently dry areas where water from surface streams appears to back up to form ponds during wet periods suggesting that the infiltration rate into the tailings may be relatively low. In the area around the sink (point E on Figure 2.2) there are former water lines suggesting that in wetter periods a fairly substantial lake forms, and there also appears to be a currently dry overflow channel that would take water from this area directly into the Frongoch Stream. On 7 February surface water in the ponds and sinking stream was frozen (Figure 2.6).

The tailings are underlain by a discontinuous peat layer which overlies glacial deposits resting on Silurian age sandstones and mudstones (Bearcock et al., 2010). It is currently unclear where groundwater infiltrating the tailings is discharged. It is likely that some of the water is discharged through the culvert (point A on Figure 2.2) which appears to be situated near the base of the tailings. Contaminated groundwater within the underlying glacial deposits suggest that some water infiltrating the tailings passes down into the glacial deposits, presumably in areas where the low permeability peat layer is absent. No substantial groundwater outlets for the glacial deposits were observed within the area of the walkover survey (Figure 2.2). Small seepages observed at points C and D may emerge from the glacial deposits.

Figure 2.1 General topography and drainage in the vicinity of the Frongoch Mine site.

The arrow indicates the previous subsurface route of water from the Frongoch Stope to the Frongoch Adit which has subsequently been diverted southwards over the surface into the Frongoch Stream.

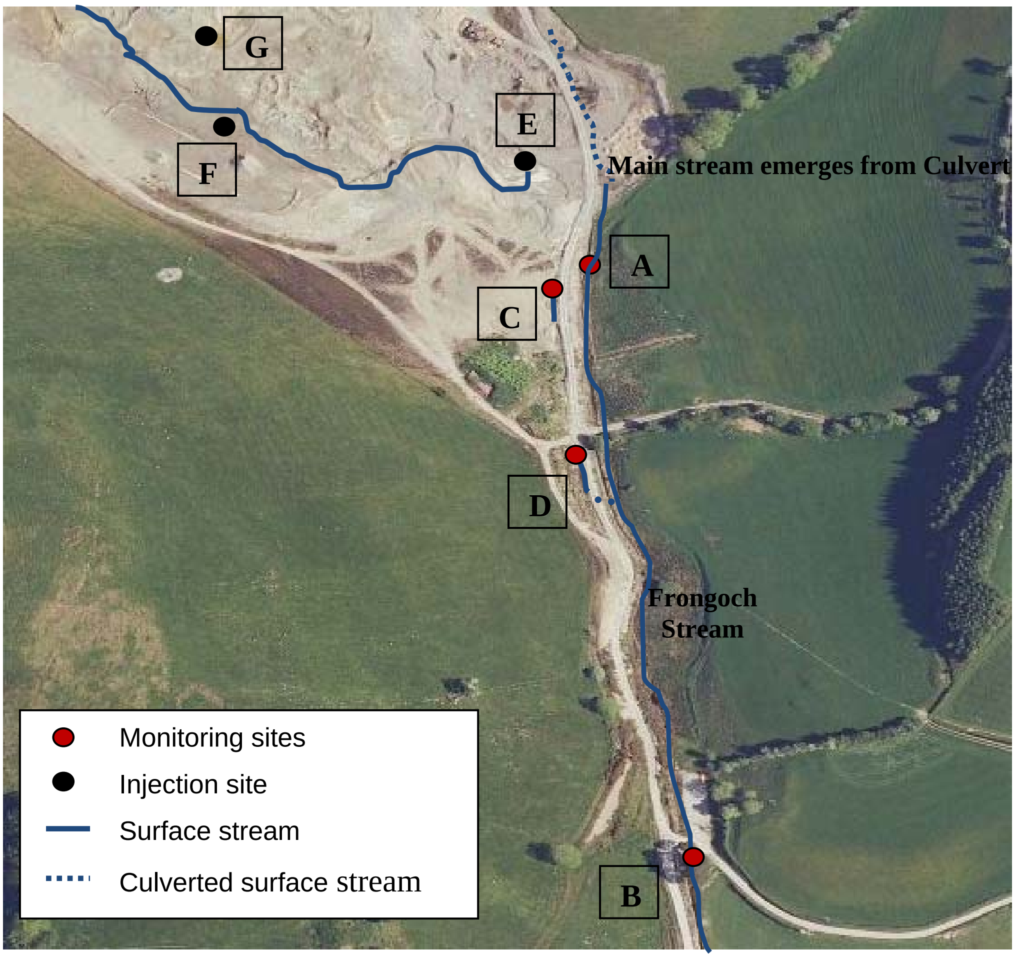

Figure 2.2 Hydrological features in the vicinity of the Frongoch Stream.

A: Culvert draining tailings, B: Frongoch Stream gauging station, C and D: Small groundwater upwellings. E: Sinking point of stream on the tailings. F: Borehole 1, G: Borehole 3

Figure 2.3 Water from the culvert entering the Frongoch stream

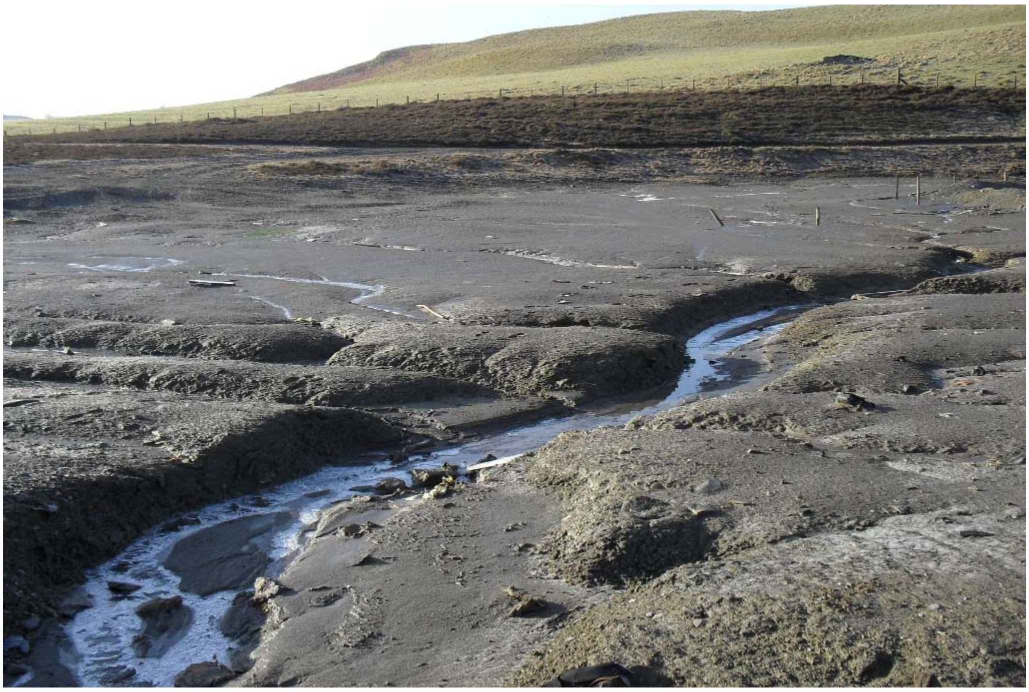

Figure 2.4 Surface stream flowing over tailings area

Figure 2.5 The surface stream sink points (6 February 2012)

Figure 2.6 The frozen stream sink (7 February 2012)

2.2 TRACER TESTING OBJECTIVES

Tracer testing offers the potential to determine whether the culvert drains groundwater from the tailings area. If a connection is demonstrated between the tailings area and the culvert, tracer testing would indicate the groundwater travel time. If a tracer breakthrough curve could be obtained, together with precipitation and flow data at the monitoring point, tracer testing could provide information on contaminant attenuation along the groundwater flowpath and how contaminant transport varies under different hydrological conditions.

2.3 POTENTIAL TRACER INJECTION POINTS

The most obvious tracer injection point is the sinking stream on the tailings area (Figure 2.5 and Figure 2.6). On 6 February 2012 the surface stream had a flow of ~ 1–2 l/s and the water was sinking into three distinct points in the ground, approximately 50 m from the culvert and at a higher elevation than the culvert. However, the area around the stream sink appears to pond in wetter conditions and it would not be possible to carry out a tracer test if the water is ponded or the stream sink is frozen. It is possible that under different hydrological conditions there would be other distinct stream sink points that could be used as tracer injection points.

The boreholes on the site could also be used as tracer injection points if there is sufficient groundwater flow. Borehole 1 (F on Figure 2.2) contains groundwater from the glacial deposits and is approximately 150 m from the culvert. Borehole 2 (G on Figure 2.2) contains groundwater from the tailings and is approximately 200 m from the culvert. Single borehole dilution tests were carried out in these boreholes during the site visit to assess their potential as injection sites (Section 3).

2.4 POTENTIAL MONITORING SITES

There are no substantial groundwater discharges in the area of the walkover survey (Figure 2.2). The culvert (point A on Figure 2.2; image in Figure 2.3) is the most suitable monitoring site and likely discharge point for water within the tailings area. The flow at the culvert is quite small (approximately 3 l/s during the field visit). It is not clear whether flow in the culvert increases during wet periods. There were also two small groundwater seepages within the base of a drainage channel to the west of the Frongoch stream at the time of the site visit (C and D on Figure 2.2). Unless there is evidence of more substantial groundwater inputs to this drainage channel in different hydrological conditions it is unlikely that tracer would be detected at these sites. The gauging station (point B on Figure 2.2) would be a good monitoring site because it would capture all groundwater inputs to the Frongoch stream and quantitative results could be obtained from this site.

3 Single borehole dilution testing

3.1 INTRODUCTION

There are two borehole piezometers containing groundwater in the area of tailings (F and G on Figure 2.2). The boreholes have diameters of 117 mm. Borehole 1 is 4 m deep with slotted casing within the bottom 1.06 m against glacial deposits. The water level was 1.85 m below the top of the external casing at 14:55 on 6 February 2012 (and therefore above the top of the slotted casing). Borehole 3 is 2 m deep and open to groundwater within the tailings through the full 2 m length. The water level was 0.72 m below the top of the external casing at 14:45 on 6 February 2012. A single borehole dilution test was carried out in both boreholes on 6 to 7 February 2012 to determine whether tracer is diluted sufficiently quickly to use them as injection points in a point to point tracer test, and to determine groundwater velocities in the tailings and in the glacial deposits.

An elevation survey carried out at the site on 10 February 2012 demonstrated that Borehole 1 is at an elevation of 236 m above Ordnance Datum (aOD). The water level is 2.73 m above the elevation of the culvert which was recorded as 231.4 m aOD. Therefore the hydraulic gradient between borehole 1 and the culvert is approximately 0.018. Borehole 1 is the only water level monitoring borehole in the glacial deposits and therefore it is unclear whether groundwater flow from the area of Borehole 1 is predominantly towards the culvert to the southeast or whether groundwater moves predominantly in a more southerly direction down the valley. Similarly, Borehole 3 is the only borehole in the tailings, therefore although groundwater level in Borehole 3 is 4.9 m above the level of the culvert, it remains unclear whether the culvert is directly down the hydraulic gradient from Borehole 3.

3.2 METHODS

The specific electrical conductance (SEC) of the borehole waters was measured using a logging probe that measures depth, temperature and specific electrical conductance (calibrated on site to 1413 µS/cm). Logs of background SEC were obtained from both boreholes. Approximately 50 grams of supermarket table salt was mixed with 250 mls of water to form a saturated saline solution. A hose was lowered to the bottom of borehole 1. The hose was filled with the saline tracer between the bottom of the borehole and the top of the slotted casing (75 mls of the saline solution), with 70 mls of deionised water added to fill the hose between the top of the slotted casing and the water table. The hose was removed from the borehole at 16:52 on 6 February 2012 to leave a column of salt tracer within the section of slotted casing. The tracer injection procedure was repeated in borehole 3 where 75 mls of the saline tracer solution was injected to fill the hose between the bottom of the borehole and the water table. The hose was removed injecting the tracer at 17:10 on 6 February 2012. Logs of specific electrical conductance were obtained from both boreholes to monitor tracer dilution.

3.3 RESULTS

3.3.1 Borehole 1

Background SEC increased slightly with depth from ~ 460 µS/cm to ~ 500 µS/cm. Following tracer injection the SEC of the borehole water was raised to ~ 44000 µS/cm. This had decreased to ~ 1025 µS/cm when the final log was measured at 13:47 on 7 February 2012. The SEC logs are presented in Figure 3.1A. Tracer dilution was exponential (Figure 3.1B).

The calculated Darcy seepage velocity was 0.23 m/d. Assuming porosities of 10% and 1% respectively, groundwater velocities in the glacial deposits in the vicinity of borehole 1 are 2.3 m/d or 23 m/d.

3.3.2 Borehole 3

Background SEC was between 482 µS/cm and 486 µS/cm. Following tracer injection the SEC of the borehole water was raised to ~ 45000 µS/cm. This had decreased to ~ 8400 µS/cm when the final log was measured at 13:50 on 7 February 2012. The SEC logs are presented in Figure 3.2A. Tracer dilution was exponential (Figure 3.2B). The calculated Darcy seepage velocity was 0.09 m/d. Porosity results calculated from bulk and particle density at 7 locations where tension infiltrometer tests were carried out ranged from 32.5 to 16.7% with a mean of 24.69%. Assuming a porosity of 25%, the groundwater velocity in the tailings in the vicinity of borehole 3 is 0.4 m/d.

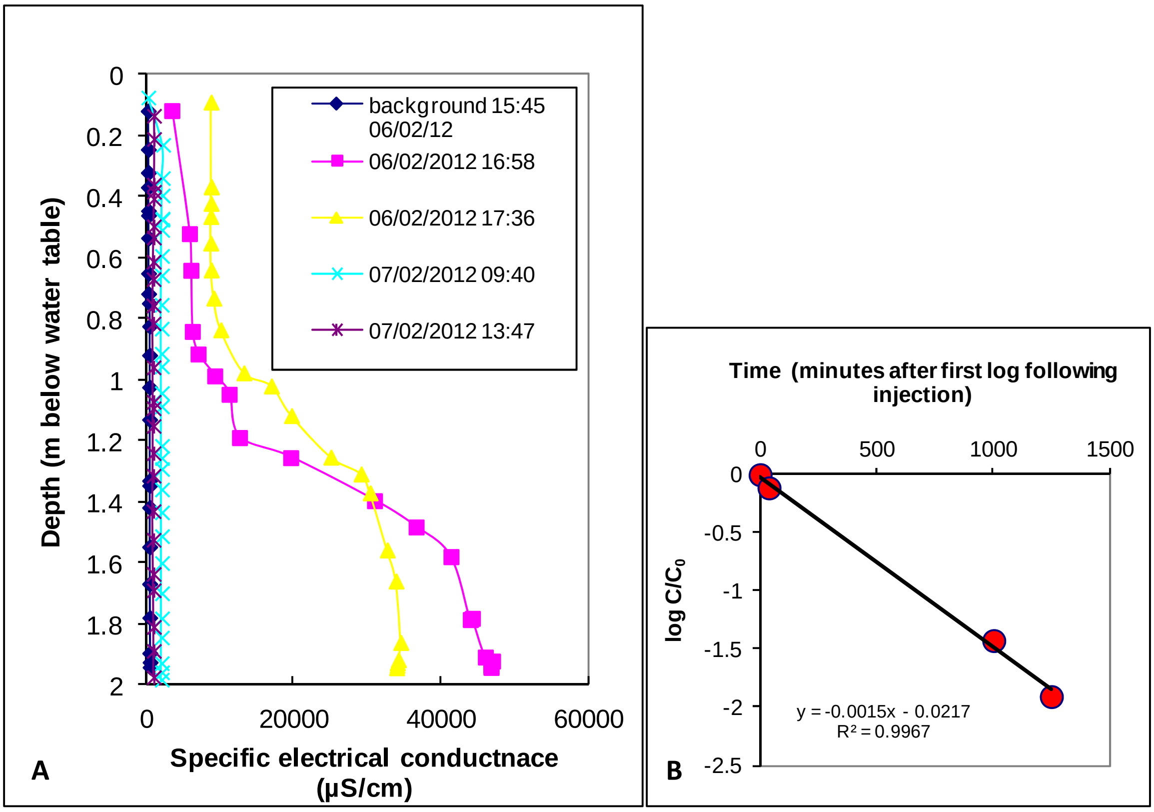

Figure 3.1 Single borehole dilution test in Borehole 1 (A: SEC logs, B: tracer dilution plot).

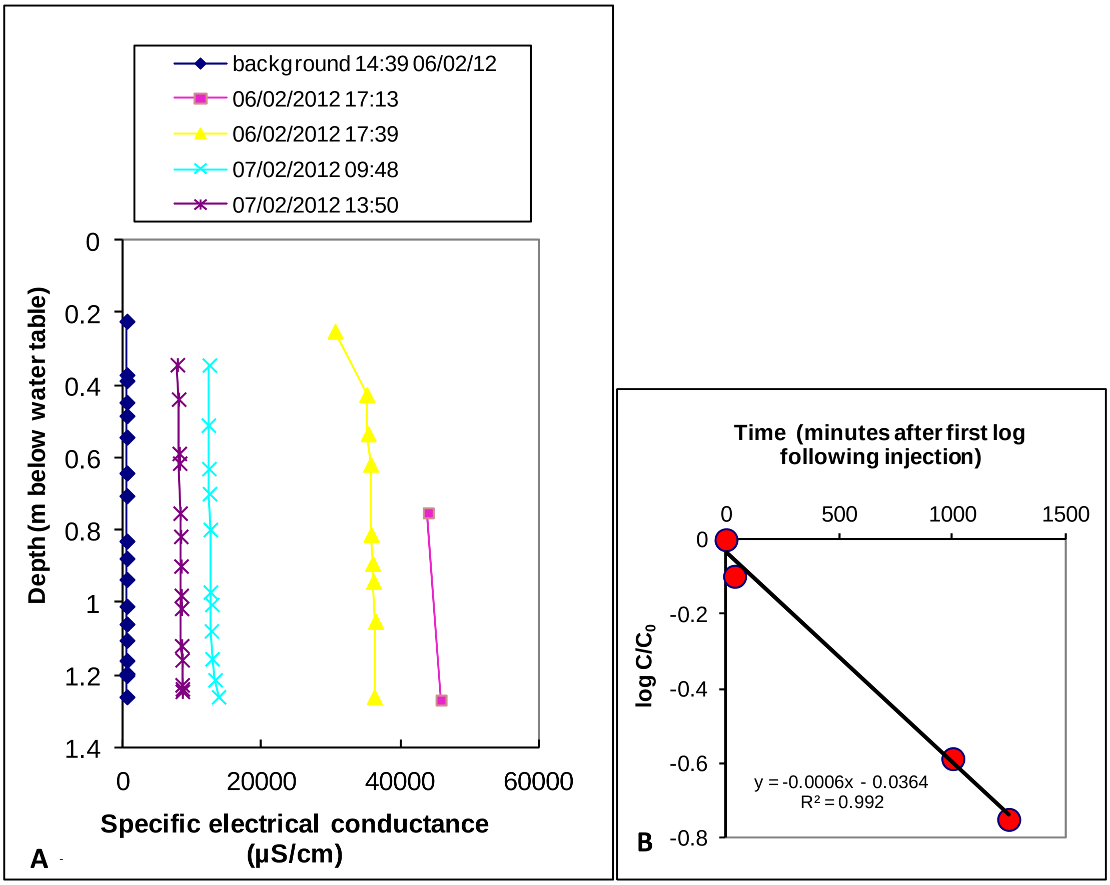

Figure 3.2 Single borehole dilution test in Borehole 3 (A: SEC logs, B: tracer dilution plot).

3.4 CONCLUSIONS FROM THE BOREHOLE DILUTION TESTING

The slow dilution times indicated by the single borehole dilution tests suggest that it is unlikely that tracer injected in the boreholes would be detected at the culvert. Groundwater velocities were higher within the glacial deposits (~2 to 20 m/d) compared to the tailings (~0.4 m/d), although there are no porosity data available for the glacial deposits and therefore there is more uncertainty in the calculated groundwater velocity. If boreholes are drilled at the site in the future, undertaking single borehole dilution tests would be a quick and simple means of investigating the variability in groundwater velocities across the site in either the tailings or the glacial deposits. Water level monitoring of additional boreholes would also indicate the hydraulic gradient across the site.

4 Suitability of Sodium Fluorescein dye at the Frongoch Mine site

4.1 INTRODUCTION

Fluorescent tracers are commonly used in groundwater tracer tests due to their generally conservative transport properties, low background presence, low toxicity and ease of measurement. Fluorescent tracers, including Sodium Fluorescein, have been used in tracer tests in mine waters or groundwaters contaminated by mine waters. However, low pH and high concentrations of Fe can cause degradation of fluorescent tracers. During the site visit samples were taken to determine: (1) Background fluorescence at potential monitoring sites; (2) Whether loss of fluorescence is likely during a tracer test at the Frongoch Mine Site.

4.2 BACKGROUND FLUORESCENCE

Samples were analysed on site using a filter fluorometer to determine background fluorescence at the Sodium Fluorescein wavelength. Background fluorescence at the culvert was very low but it was high at the Frongoch gauging station (Table 1).

Table 1 Background Sodium Fluorescein concentrations

Sample	Sodium Fluorescein (mV)	Sodium Fluorescein (µg/l)
Milli-Q water	0.58	0.01
Frongoch stream gauging station (7 Feb 2012)	3.13	0.98
Culvert (7 Feb 2012)	0.68	0.01

4.3 LOSS OF FLUORESCENCE

Standard solutions of approximately 38 µg/l and 380 µg/l were made up using deionised water, water from the culvert, and water pumped from borehole 1. The 38 µg/l standards were measured in the field using a filter fluorometer. The fluorescence was lower in the standards made with water from borehole 1 and the culvert than that made with deionised water (Table 2). Analysis of the 38 µg/l and 380 µg/l standards in the laboratory on a spectrofluorometer confirmed lower fluorescence in the standards made using water from borehole 1 and the culvert compared to those made using deionised water, and indicated that around 75% of the fluorescence was lost in the standards made with water from borehole 1 and the culvert.

Table 2 Impact of Frongoch groundwaters on fluorescence measured by filter fluorometer

Sample	Sodium Fluorescein (mV)	Sodium Fluorescein (µg/l)
38 µg/l standard deionised water	82.97	38.26
38 µg/l standard Borehole 1 (7th Feb 2012)	67.08	29.52
38 µg/l standard Culvert (7th Feb 2012)	59.45	28.12

4.4 CONCLUSIONS ON THE SUITABILITY OF SODIUM FLUORESCEIN FOR TRACING

Due to the decrease in fluorescence of Sodium Fluorescein when it comes into contact with the groundwaters at the Frongoch site, it cannot be recommended for use at this site. It is possible that another dye tracer might be more suitable (e.g. Amidorhodamine G). However, bacteriophage tracers are likely to be a better alternative, as they are highly detectable tracers that may not be affected by the metals present in the groundwater. Any tracer should be tested in contact with the groundwaters at the site before a tracer test is carried out.

5 Conclusions and recommendations

5.1 HYDROGEOLOGY OF THE TAILINGS AREA

Available evidence suggests that groundwater flow velocities and permeability of the tailings area are generally quite low. Single borehole dilution tests indicate fairly low groundwater velocities of ~ 0.4 m/d in the tailings. Surface channels and ponds are common on the tailings area, and it appears that during wet periods there is considerable accumulation of surface water in ponds which either overflow to enter the Frongoch stream directly or which gradually infiltrate the tailings area. The temperature of the water in the culvert was 8.9ºC on 7 February 2012, which was similar to that in borehole 1 (the glacial deposits) which was 8.8ºC. This is considerably warmer than the temperature in borehole 3 (the tailings) which was approximately 4.9ºC. This suggests that the water in the culvert has a longer groundwater residence time, perhaps at depths of more than 2 m below the surface, and that the water may come from the glacial deposits rather than the tailings.

A distinct stream sink was observed during the site visit (Section 2), and it is possible that there are other distinct sink points present within the exposed tailings area under different hydrological conditions. Visual observations during the site visit suggest that the amount of water sinking into the tailings from the surface stream (~1-2 l/s) is similar to the amount of water discharged from the culvert (~ 3 l/s). There may be additional water sinking through the base of the surface stream before it reaches the main sink point. It is possible that there could be a preferential flowpath between the sinking stream and the culvert which could result in a rapid groundwater velocity (hours). However, the area around the stream sink appears to pond in wetter conditions suggesting that the infiltration capacity of the stream sink is limited.

If further boreholes are drilled at the site, additional single borehole dilution tests would be a simple method of obtaining information on the variability in groundwater flow rates across the site, and water level monitoring would provide information on the groundwater hydraulic gradient across the site.

5.2 TRACER TESTING

5.2.1 Design of tracer test

Tracer testing between the sinking stream on the tailings and the culvert would have a reasonable likelihood of being successful. A successful tracer test would indicate the travel time and would determine whether there is a rapid preferential flowpath between the stream sink and the culvert or whether the flow rate is slower and similar to that encountered in Borehole 3. If tracer breakthrough curves could be obtained at the Frongoch stream gauging station, tracer mass balance could be calculated and variability in flow rates and contaminant transport under different hydrological conditions could be investigated. If such an experiment is carried out, sampling should be undertaken at the culvert and at the Frongoch gauging station.

5.2.2 Tracer type

The use of Sodium Fluorescein tracer is not recommended at the site due to the reduced fluorescence once the dye has been in contact with the metal contaminated waters. Experiments could be carried out to determine if there is a loss of fluorescence of other dye tracers (e.g. Amidorhodamine G). A better solution would be to use bacteriophage tracers which are highly detectable and are less likely to be affected by metals within the groundwater. Any tracer should be tested in groundwaters from the site prior to a tracer test to determine that it is not degraded by the contaminants present.

Reference

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