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Hydrogeochemical observations to improve site characterisation and remediation of Frongoch Mine, Wales

Groundwater Science Programme

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Hydrogeochemical observations to improve site characterisation and remediation of Frongoch Mine, Wales

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Front cover

View of Frongoch Mine.

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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 reviews the EA and BGS hydrogeochemical data available to date in order to inform the refinement of the site conceptual model.

Acknowledgements

The authors thanks Paul Edwards from the Environment Agency (EA) for providing the EA data and Helen McGann (EA) for assistance during field visit. The authors would like to thanks Mr J. Bray, the landowner, for site access.

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Summary

This report, commissioned by the Environmental Agency, presents a review of the hydrogeochemistry of the Frongoch Mine, an abandoned metal mine 17 km south east of Aberystwyth, Ceridigion, mid Wales. The mine produced lead and zinc ore from 1798 until its closure in 1904. The abandoned mine spoils and mine adit discharges cause severe adverse impacts on the receiving watercourses, the major contaminants being Zn and Pb.

The main objectives of the study were to:

1. Present EA and BGS water monitoring data collected from 2003 to 2011 to provide a basis for documenting the likely effects of future remedial actions on Zn and Pb concentrations.
2. Evaluate the effects of the stream diversion upstream of the Frongoch mine tailings area on flow, metal concentrations and loads of the waters impacted by the mine discharges.
3. Use mass balances for quantifying source loadings with particular regards to the Frongoch Stream, immediately downstream the mine waste area.
4. Constrain the hydrogeochemical framework, based on the available flow monitoring data, chemistry and rainfall data.

The EA monitoring sites include the two main mine water issues, respectively, the mine water discharge at the Frongoch Adit portal (Frongoch Adit) and the tailings lagoon discharges via a culvert to the stream adjacent the area of mine spoils, referred to as the Frongoch Stream; upstream monitoring sites; surface water from the mine spoil area; and the Nant Cwmnewydion and Nant Cell, both tributaries of the Afon Ystwyth and both watercourses impacted by Frongoch Mine.

Remedial measures already undertaken in the vicinity of the mine workings include the modification of an existing pond to divert the surface water that would formerly have overflowed into the mine workings. Water entering the mine workings is drained in a south-westerly direction to the Frongoch Adit at SN 713 742, which discharges to the Nant Cwmnewydion. The water from the diversion channel is drained to a perimeter ditch on the eastern side of the Frongoch site (Frongoch Stream), which discharges to the Nant Cell. The effects on the Frongoch Stream and Frongoch Adit of the diversion of water away from the Llwyn Shaft towards the Frongoch Stream in February-March 2011 can be summarised as follows:

Stream diversion effects on flow

The stream diversion has, as expected, increased the flow of the Frongoch Stream (average flow of 17 l/s from 2004 to 2008 and 62 l/s from March 2011 to February 2012) and reduced the average water flow at the Frongoch Adit portal (average flow of 87 l/s from 2004 to 2008 and 25 l/s from March 2011 to February 2012).

Stream diversion effects on concentrations and loads

The Frongoch Adit discharge showed a sustained increase in both Zn and Pb concentrations, immediately after the diversion of water away from the Llwyn Shaft and in response to the reduced flow at the adit portal. However, since December 2011 the concentrations have started to gradually decrease. The loadings post-diversion are similar to previous loadings. Although the water quality of the Frongoch Stream has significantly improved as a result of dilution, the Zn and Pb loads in the Frongoch Stream have not changed, on average, since the diversion.

Mass balance calculations using EA data have identified the culvert discharge, draining groundwater from the mine spoil/tailings area, as the major input source of Zn to the Frongoch Stream. Its contribution was calculated as ~ 80% of the Zn fluxes during sampling in a high flow regime (22/09/2011), following a fortnight of intense rainfall. During very low flow conditions

of the culvert discharge, assuming a flow ranging between ~ 0.5 l/s and 0.8 l/s, the contribution to the Frongoch Stream remained large, estimated as ~ 60 to 90% on 15th July 2011. On the 22nd August 2011, assuming a flow as low as 0.3 l/s, the culvert contributed 90% of the Zn fluxes in the Frongoch Stream. For all those cases, a considerable unsampled source of Pb loading to the Frongoch Stream, other than the culvert, was highlighted. It is probable that the EA-labelled "surface water from Frongoch tailings" samples, which are considerably higher in Pb and lower in Zn than the culvert discharge, contribute to the additional input to the Frongoch Stream. The "surface water" sampled by the EA (Site ID 35600) consists of a very small flow emerging from the southern end of the site, into the base of a drainage channel running along the west side of the road parallel to the Frongoch Stream, to the south of the culvert. It is plausible that this is a discharge point for groundwater that collects to the south of the culvert. The observed enrichment in Pb warrants further investigation.

Considerable surface run-off during storm events has been observed in various occasions. However, the available dataset does not include monitoring data during storm events to allow quantification of the likely significant runoff component of metal loading to the Frongoch Stream.

A mass balance for the Zn and Pb loadings in the Nant Cell was calculated using BGS unpublished data. A marsh area was identified as a contaminant store, but a more detailed study is needed to characterise this.

Whilst the sampling frequency is often insufficient to develop hydrogeological models that lack uncertainty, there is sufficient data to draw some broad conclusions that account for observed water chemistries:

Frongoch Adit

A previous assessment of the daily gauged flow and rainfall data undertaken by Atkins indicated a rapid response to rainfall at the Frongoch Adit, with flow peaks appearing 1-2 days after a storm event and dropping off rapidly thereafter. A scenario of an open mine system with high temporary storage but limited baseflow from deeper groundwater was suggested. Based on the available flow monitoring data, rainfall data and chemistry, the 'flashy' response to rainfall with flow rising quickly and then subsiding more gradually still occurs. The analysis of Pb and Zn concentrations and flow at various times indicates that the concentrations are generally lower when there are high flows until March 2011, as a probable effect of dilution during freshwater ingress in the underground mine system. Thereafter, the first peak in flow after a long period of low flow corresponded to unvaried concentrations of Pb and Zn, to suggest the flushing out by dissolution of the secondary minerals accumulated within the dewatered workings, able to overcome dilution effects.

Frongoch Stream

Comparison of the concentration and flow data on various dates does not show a constant relationship between the two measurements, i.e. high stream flows do not always correspond to the lowest metal concentrations, as would be expected from dilution effects, but, likewise, high flows do not always correspond to high metal concentrations, as indicative of a significant dissolved metal contribution to the stream through surface runoff. It is likely that the reason for non-unique response between flow and concentrations is due to the influence of the antecedent rainfall regime preceding the sampling event, which affects the infiltration/runoff ratio and consequently the potential for leachable metals to be flushed out into the stream. This makes comparison of stream concentrations for similar flow conditions difficult.

In order to constrain the hydrogeochemical framework for the mine waste spoils the following have been considered:

- The mine waste spoils host a Zn and Pb contaminated water table aquifer which has been sampled through borehole BH3 and which shows a significant seasonal trend in Zn concentration, with much higher Zn in the warm sampling months as a result of evaporation.
- A deeper groundwater in the underlying clayey till was sampled through borehole BH1. It is consistently lower in Pb with similar or lower Zn concentrations than BH3. Its chemistry shows low seasonality for Zn, while the Pb content is higher in the sampling events corresponding to the cold months. It has been previously suggested that the metal concentrations in groundwaters sampled via the deep borehole BH1 are evidence of the contaminated plume infiltrating the tailings and the peat layer to the underlying glacial till. Despite the plausibility of the infiltration model, an alternative hypothesis of a different source for this water cannot be completely discounted.
- During the rather limited and discontinuous monitoring period 2009 until February 2012, the culvert at the south east corner of the Frongoch tailings area had Zn concentrations ranging between 66700 μgL-1 and 239000 μgL-1 (average 94600 μgL-1) and Pb concentrations ranging from 1690μgL-1 to 8970 μgL-1 (average 3740 μgL-1). Based on the available data, the winter months were on average the months with the lowest concentrations of both Zn and Pb, while the highest concentration peaks were recorded for Zn mostly in the summer months and for Pb in spring/summer, and were associated with flows lower than 1 l/s. There is a strong positive relationship between metal load and flow of the culvert discharge. Based purely on the Pb concentration trends, it appears that the perched water represented in BH3 drains into the culvert, while hydrological connectivity between BH1 and the culvert is less probable. However, the distinct Zn enrichment in BH3 in the July sample was only marginally evident in the culvert seepage. The lack of coincidence in peak contaminant concentrations between borehole groundwater and culvert discharge samples may suggest long residence time or perhaps preferential subsurface flows in the spoils.
- Discharge at the culvert can peak in response to rain events. Previous single borehole dilution tests (Maurice et al., 2012) indicated a low groundwater velocity of ~ 0.4 m/d in the tailings around borehole BH3. However, it is possible that a proportion of water in the tailings moves relatively quickly through preferential flow and could account for the relatively flashy hydrograph response to rainfall. This is favoured during wet antecedent conditions. Another explanation would be the piston effect, i.e. the head transmission through the aquifer can cause displacement of stored water. However, the lower metal concentrations at the culvert discharge on those high flow events seem to favour the hypothesis of bypass flow. Flow at the culvert, although very low (< 1 l/s), continued even during dry periods (e.g. April 2011), suggesting a matrix flow moving relatively slowly through the waste.

Overall the observed differences in chemical trends of Zn and Pb, sampled from BH1 and BH3 during different seasons, and comparisons between the culvert seepage composition and groundwater give insights on the heterogeneous chemical, mineralogical and textural nature of these spoils, which has been highlighted in previous BGS studies. This heterogeneity can give rise to preferential subsurface flow paths, which may be activated in response to differing water table elevations and therefore following seasonal changes in recharge. It can differently enrich the groundwater chemistry depending on the water table height in relation to certain enriched mineral horizons.

1 Introduction

Following a site visit (14 December 2011) to the Abandoned Mine at Frongoch Mid-Wales with staff from the Environment Agency (EA) and Atkins, the British Geological Survey (BGS) were invited to assist in furthering the development of the ground model (GM) for the tailings lagoon and the mine.

Frongoch Mine [NGR SN 72200 74400] is an abandoned lead-zinc mine in the Ystwyth catchment, mid-Wales, UK, and is one of 50 Welsh sites prioritised by the Environment Agency for remediation (Contains Ordnance Survey data © Crown Copyright and Database rights 2012. Licence No. 100021290

Figure 1.1). The mine occupies a valley setting. The solid geology comprises interbedded sandstone and mudstones. Till covers the valley bottom. As well as capping the higher ground, peat forms a natural mere in the valley bottom where it is underlain by the till. The mineralization, and hence the mining, was focused on east-north-east trending normal faults, situated immediately to the north of the mere and at a marginally higher elevation. The natural slope of the ground was utilised for mine processing, which facilitated the use of the mere as a tailings lagoon. The results of a geophysical survey (electrical resistivity tomography) indicate the possible presence of contaminated groundwater below the level of the till (highly conductive zone) (Kuras et al., 2011). It is possible that this is groundwater that occupies a zone of scree, or frost shattered bedrock.

Remedial measures already undertaken in the vicinity of the mine workings include the modification of an existing pond to divert the surface water run-off that would formerly have entered the Llwyn Shaft open workings and drained in a south-westerly direction to the Frongoch Adit at SN 713 742. The Frongoch Adit discharges to the Nant Cwmnewydion a tributary of the Afon Ystwyth. The water from the diversion channel is drained to a perimeter ditch on the eastern side of the Frongoch site and referred to as Frongoch Stream, which discharges to the Nant Cell, a tributary of the Afon Ystwyth. The stream diversion took place in February-March 2011. Zinc contaminated drainage from the tailings lagoon discharges via a culvert at SN 723 741 to the same surface water course, so the addition of the water from the new lagoon serves to dilute the tailings lagoon discharge. There is also a surface water run-off component to the discharge in the Frongoch Stream, much of which passes across the tailings lagoon.

The proposed remedial works for the site were detailed in the Remediation Options Feasibility Assessment report (Atkins, 2011) and essentially comprise the construction of perimeter ditches and a cover for a significant proportion of the tailings lagoon. The BGS were invited to assist in revisiting the conceptual site model of the site. One of the key uncertainties lies in understanding the extent of groundwater in the area of the tailings lagoon.

This report reviews the EA and BGS hydrogeochemical data available to date at Frongoch Mine and it is part of a series of BGS reports aimed to the refinement of the site conceptual model (Humpage and Banks, 2012; Maurice et al., 2012; Palumbo et al., 2012; Shaw, 2012).

The main objectives of the study are to:

1. Present EA and BGS water monitoring data collected from 2003 to 2011 to provide a basis for documenting the likely effects of future remedial actions on Zn and Pb concentrations.
2. Evaluate the effects of the stream diversion upstream of the Frongoch mine tailings area on flow, metal concentrations and loads of the waters impacted by the mine discharges.

3. Use mass balances for quantifying source loadings with particular regards to the Frongoch Stream, immediately downstream the mine waste area.
4. Constrain the hydrogeochemical framework, based on the available flow monitoring data, rainfall data and chemistry.

Figure 1.1 General topography and drainage in the vicinity of the Frongoch Mine site.

1.1 AVAILABLE DATA

1.1.1 EA data

The hydrochemical dataset comprises historical data collected by the EA at 13 monitoring locations (Figure 1.2). The monitoring period varies from location to location, dating from 1977 for some of the sites, but more recently (with monitoring windows in 2007, 2009 and to date) for most sites (Table 1.1). Each location is generally sampled once a month, although the frequency can be quarterly, bimonthly or less frequently. There is no set sampling date within each month. A summary of the sampling frequency is presented in Table 1.1.

Some spot flow gauging data (reported as m^3/s or l/s) are available, although not for all the monitoring events. For the Frongoch Adit portal some continuous flow gauging data are also available for the period 7/2/2011 to 30/01/2012. A significant discrepancy between the spot flow gauging and correspondent continuous flow gauging measurements has been noticed. As the reason for this discrepancy has not been resolved, uncertainties remain regarding the flow and related contaminant fluxes at the Frongoch Adit portal. The data are reported separately and a range of possible load estimates based on the two flow gauging measurement types described.

Daily average rainfall data for the period January 2007- January 2012 have been obtained for a monitoring station in Cwm Rheidol, approximately 5km north of Frongoch.

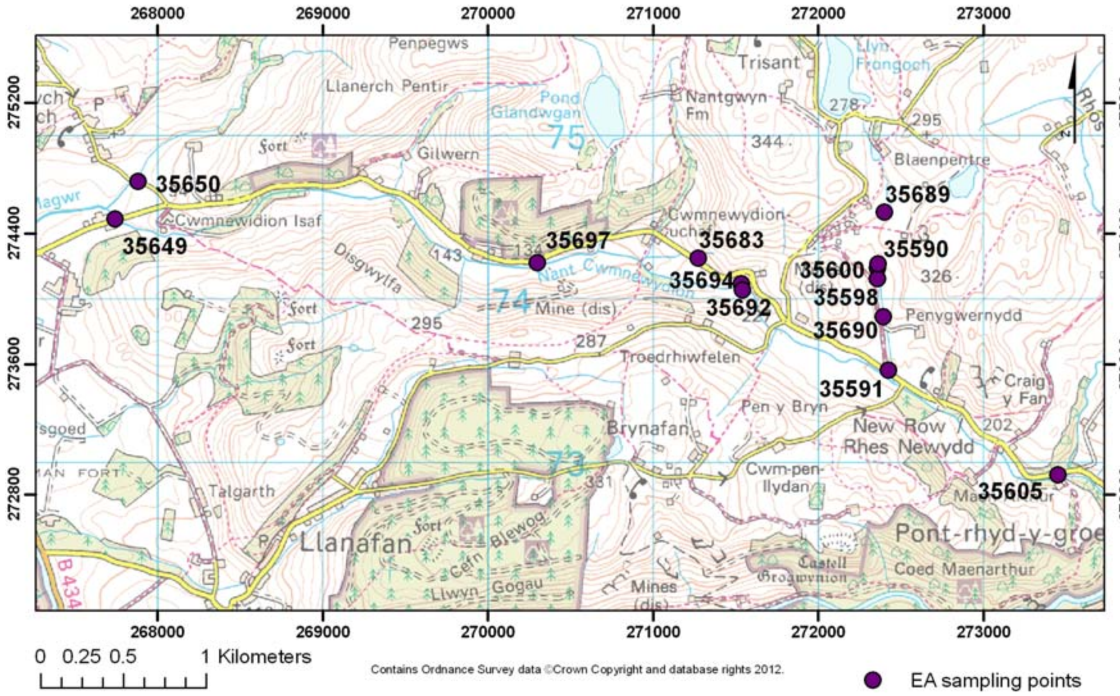


Figure 1.2 EA monitoring points, for a key to the site numbers, see Table 1.1

Table 1.1 EA monitoring sites around Frongoch

EA monitoring ID	National Grid Reference	Site Description	Sampling frequency
35605	SN7344972924	Frongoch Stream above confluence with Nant Cell	Quarterly to twice monthly (Apr 1977- Feb 2012)
35649	SN6774074490	Nant Cwmnewyddion u/s Magwr confluence	Approximately monthly (March 1978 and Jun 2011-Feb 2012)
35692	SN7153474094	Mill Race Stream at confluence with Nant Cwmnewyddion	Approximately monthly (Jan 2007-Feb 2012)
35694	SN7154174056	Nant Cwmnewyddion u/s confluence with Mill Race	Approximately monthly (Jan 2007-Feb 2012)
35598	SN7235674192	Culvert on Frongoch tailings	Approximately monthly (March 2009-Feb 2012)
35600	SN7235974124	Surface water from Frongoch tailings	Approximately monthly (Dec 2009-Feb 2012)
35683	SN7127374251	Frongoch Adit portal at gaugeboard	Approximately monthly (March 1978 and Jan 2003-Feb 2012)
35690	SN7239373891	Frongoch Stream d/s mine at gaugeboard	Approximately monthly (July 2004-Feb 2012)
35650	SN6788074720	Afon Magwr u/s confluence with Cwmnewyddion	Approximately monthly (March 1978 and Jun 2011-Feb 2012)
35697	SN7030074221	Nant Cwmnewyddion d/s mine site	Approximately monthly (Jan 2007-Feb 2012)
35689	SN7240174530	Input to pond (no longer sampled)	Approximately monthly (July 2004-Dec 2009)
35590	SN7236274214	Frongoch Stream u/s culvert	Approximately twice monthly (Jan 2012-Feb 2012)
35591	SN7242573565	Frongoch Stream u/s road	Approximately twice monthly (Jan 2012-Feb 2012)

1.1.2 BGS data

Data collected by BGS between 2006 and 2009 are reported in Bearcock et al. (2010) and shown in Figure 1.3. The sites and sampling dates are presented in Table 1.2. In addition, the Culvert, Surface Runoff, Mill Pond, Adit, borehole 1 and borehole 3 were sampled on a visit on 09/03/2011.

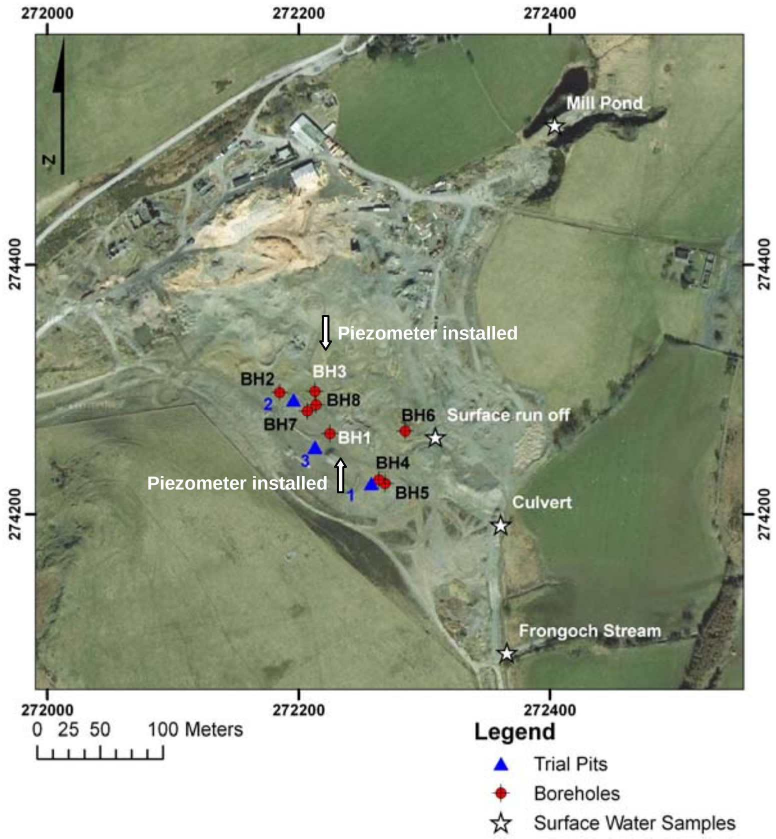


Figure 1.3 BGS sampling sites (the Frongoch Adit (SN 713 742) remains outside the plotting area to the west of the site) (Aerial photography © Getmapping Licence No. UKP2006/01).

Table 1.2 Samples taken on each visit to Frongoch (Bearcock et al., 2010)

Site	Unique Lab ID	Easting	Northing	Sampled
Trial Pit 1	11475-0001	272258	274225	08/08/2006
Trial Pit 2	11475-0002	272196	274292	08/08/2006
Trial Pit 3A	11475-0003	272213	274254	08/08/2006
Trial Pit 3B	11475-0004	272213	274254	08/08/2006
Stream	11944-0001	272366	274089	30/07/2008
Culvert	11944-0002	272361	274192	30/07/2008
BH1	11944-0003	272225	274265	30/07/2008
BH3	11944-0004	272213	274299	30/07/2008
BH7	11944-0005	272214	274288	30/07/2008
Culvert	12093-0005	272354	274173	03/03/2009
Surface Runoff	12093-0006	272309	274262	03/03/2009
Mill Pond	12093-0007	272404	274512	03/03/2009
Adit	12093-0008	271251	274282	03/03/2009
BH1	12093-0001	272224	274263	03/03/2009
BH3	12093-0002	272215	274295	03/03/2009
Culvert	12188-0002	272354	274173	29/07/2009
Surface Runoff	12188-0013	272289	274257	30/07/2009
Mill Pond	12188-0001	272404	274512	29/07/2009
Adit	12188-0004	271251	274282	29/07/2009
BH1	12188-0008	272224	274263	30/07/2009
BH3	12188-0006	272215	274295	30/07/2009

2 Temporal trends of concentrations, discharges and metal loading

The available time series data were reviewed for four of the monitoring locations: 1) the Frongoch Adit portal (EAW 35683); 2) the Frongoch Stream downstream of the mine (EAW 35690); 3) the Frongoch culvert draining the Frongoch mine waste area (EAW 35598); 4) the surface water sampled from the mine tailings (EAW 35600) (Contains Ordnance Survey data © Crown Copyright and Database rights 2012. Licence No. 100021290

Figure 1.1 and Figure 1.2). These represent the known sources of metal inputs, related to the Frongoch Mine, to the Nant Cwmnewydion (the Frongoch Adit) and to the Nant Cell (the Frongoch Stream/ culvert/surface water), both tributaries of the river Ystwyth.

The data collected over discontinuous monitoring periods starting from 2003/2004 to 2011/2012 provide a basis for documenting the effects of the stream diversion which took place in February/March 2011 and of future remediation measures on metal concentrations.

2.1 THE ADIT PORTAL (EAW 35683)

The dataset comprise chemical data collected monthly from January 2003 to September 2003 and from July 2004 to July 2005; 11 data points were collected monthly between February and December 2007, and data was collected mostly on a monthly basis between December 2008 to January 2012. One monitoring point in March 1978 is also available.

2.1.1 Pre- and post- stream diversion changes in flow

Figure 2.1 compares the available spot flow gauging measurements (22/03/2012 to 3/02/2012) and the continuous flow gauging measurements (7/02/2011 to 30/01/2012) from the Frongoch Adit. The spot and daily gauging are plotted at the same scale on Figure 2.1. Comparison of the two datasets indicates that the continuous gauged data is consistently higher than the spot gauge data. This may relate to an error in either the rating curve or the method of measurement. The uncertainty related to the discrepancy between the two types of measurements remains unresolved at this stage. Therefore, both data types are considered separately in the following paragraphs.

Figure 2.2 shows the spot flow gauging measurements available for the Frongoch Adit portal. The data indicate much higher flows issuing from the adit during the monitoring periods 2004-2005 and 2007-2008 (average measured flow of all the available data from 2004 to 2008 = 87 l/s), than during the last monitoring period (March 2011 to present; average flow = 25 l/s). This last monitoring period corresponds to the post-stream diversion period and therefore these values are likely to indicate the pre- and post-diversion changes in flow.

Similarly, using the continuous flow monitoring data (Figure 2.1) it is possible to highlight the significant decrease in flow from 249 l/s at the start of the continuous monitoring in early February 2011 to 118 l/s on the 26/02/2011. After reaching a steady-state low value, at least until early June 2012 (monitoring gap between 8/6 and 16/9), the flow increased again from September, although never reaching the pre-stream diversion values.

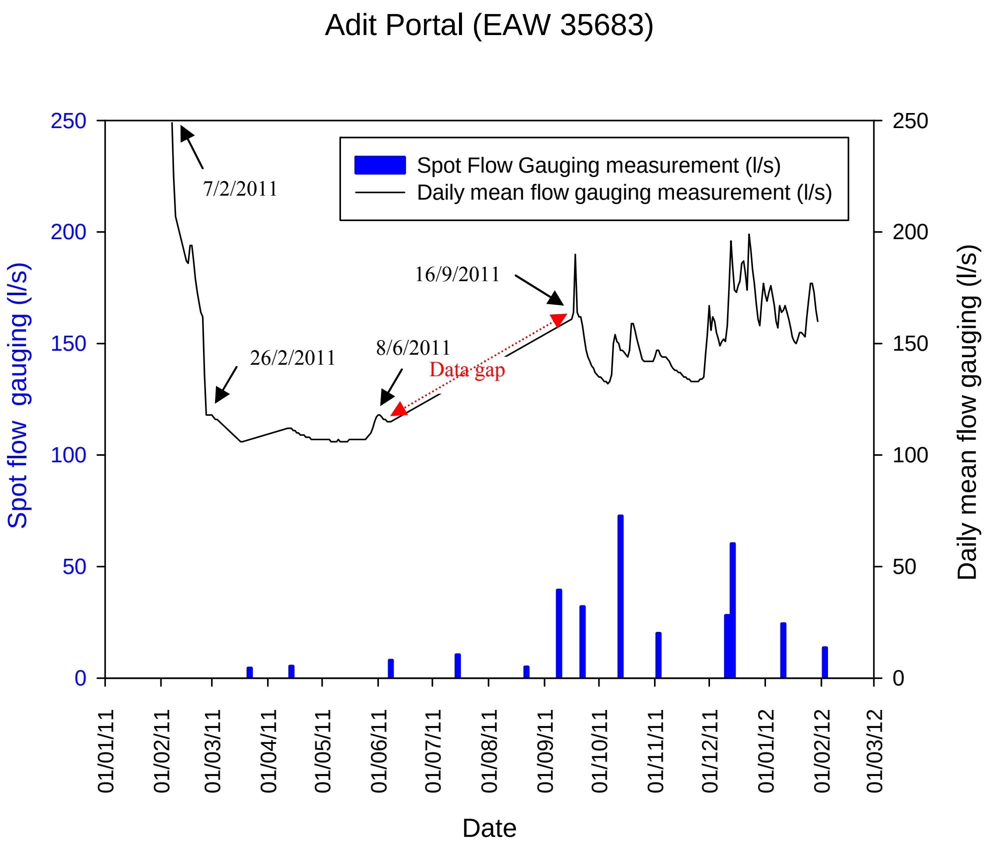


Figure 2.1 Comparison between the spot flow gauging measurements (22/03/2012 to 3/02/2012) and the continuous flow gauging measurements (7/02/2011 to 30/01/2012) from the Frongoch Adit.

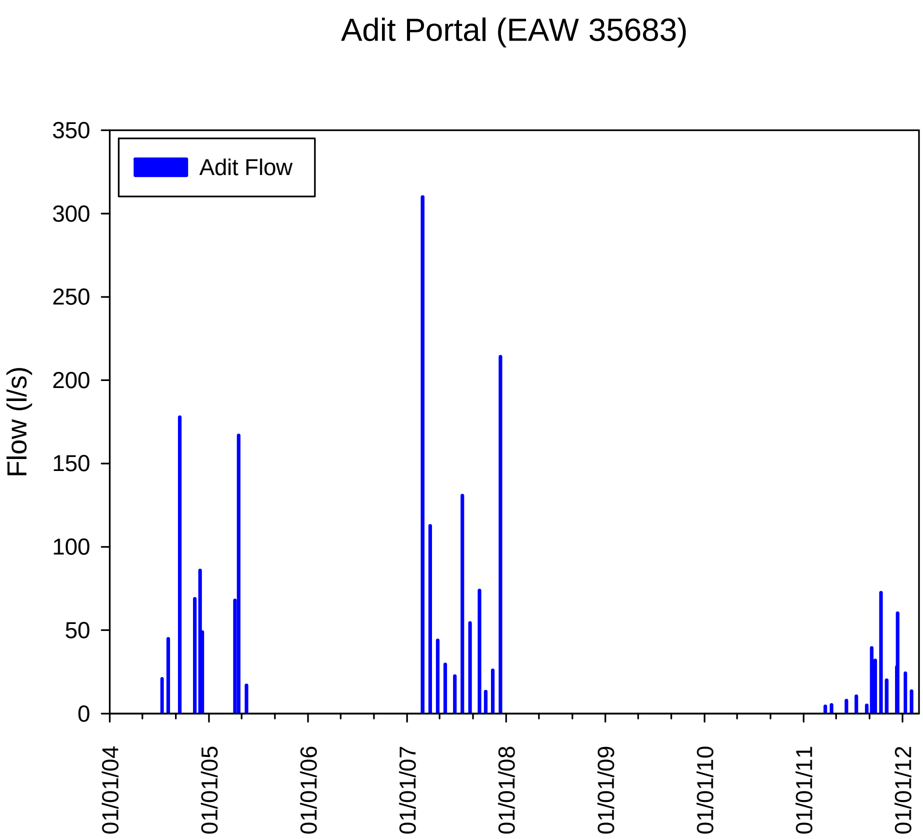


Figure 2.2 Flow measurements from the Frongoch Adit 2004 – 2012.

2.1.2 Pre- and post-diversion changes in water quality

Concentration data (µg/l) for Pb and Zn in the water issuing from the Frongoch Adit have been assessed by plotting them over the monitoring period 16/1/2003- 3/2/2012 (Figure 2.3). Prior to the stream diversion Pb concentrations ranged between 666 (µg L^{-1}) and 220 (µg L^{-1}) and Zn concentrations between 9120 (µg L^{-1}) and 2520 (µg L^{-1}). Broadly, the fluctuations in Pb and Zn correlate with each other. The most rapid and sustained increase in Pb and particularly Zn concentrations occurred immediately after the diversion of water away from the adit, in correspondence of a lower flow and therefore as probable effect of less dilution. Pb increased from 281 µg L^{-1} prior to the stream diversion (December 2009), to a peak of 820 µg L^{-1} in December 2011 and similarly, Zn increased from 3060 µg L^{-1} to 15600 µg L^{-1} over the same time period. Water quality has slowly improved since, with concentrations of 633 µg Pb L^{-1} and 12900 µg Zn L^{-1} on 03/2/2012.

The analysis of Pb and Zn concentrations and flow on various dates indicates generally lower concentrations at high flows until March 2011, as probable effect of dilution during freshwater ingress in the underground mine system. Thereafter, the first peak in flow after a long period of low flow corresponded to unvaried concentrations of Pb and Zn, suggesting the secondary minerals accumulated within the dewatered workings have been flushed out by dissolution, overcoming dilution effects (Figure 2.4).

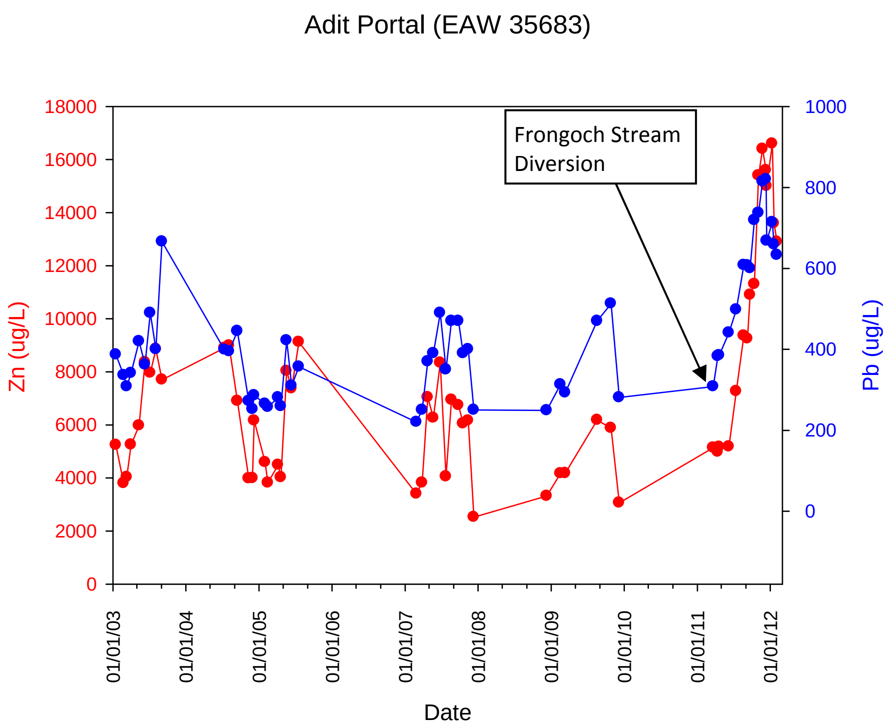


Figure 2.3 Concentration of Pb and Zn in the water draining from the Frongoch Adit.

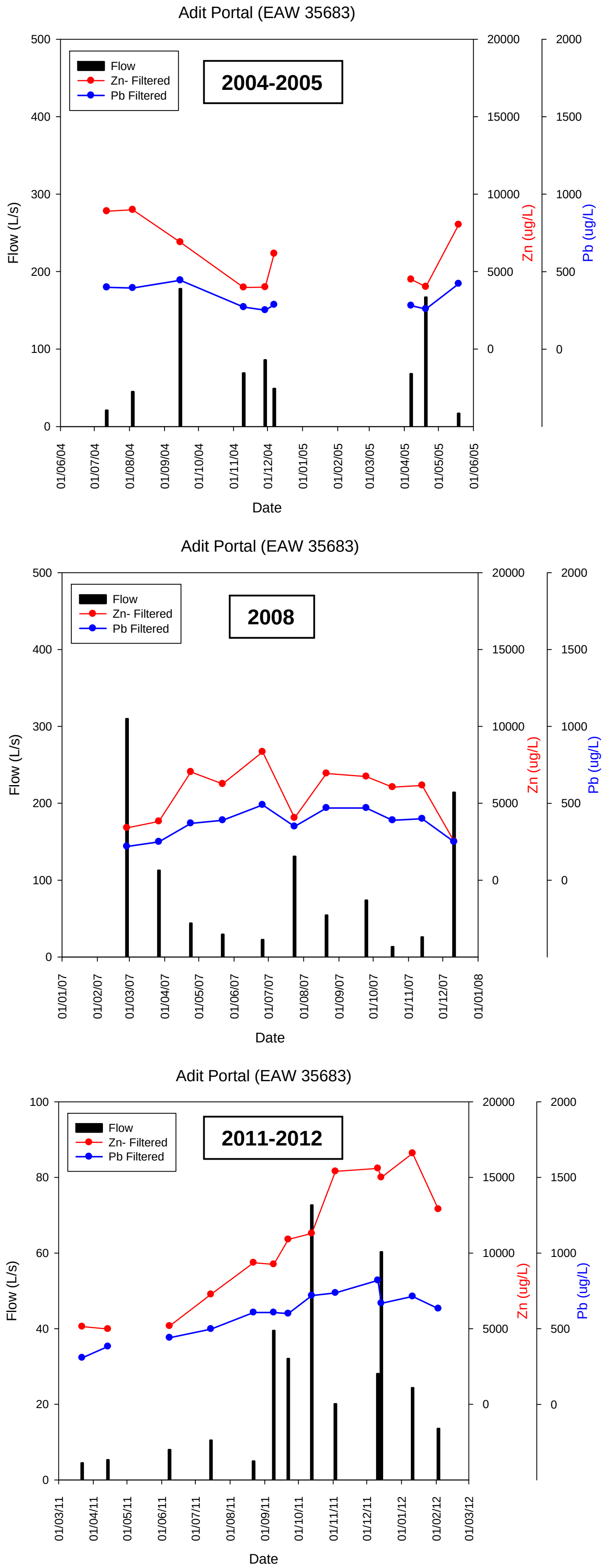


Figure 2.4 Concentrations of Zn and Pb presented with flow of the adit discharge at varying monitoring times.

2.1.3 Pre- and post-diversion changes in metal loading

Table 2.1 reports the loadings of Pb and Zn in the adit discharge, using both spot and continuous flow measurements.

Figure 2.5 shows the loadings of Pb and Zn in the adit discharge, using the spot flow measurements. Unlike the concentration trends (Figure 2.4), the loadings post-diversion are not too dissimilar to previous loadings.

Prior to the diversion (July 2004–December 2007, n = 20) the average Pb load was 2.33 kg day^{-1}, the range was between 0.45 kg day $^{-1}$ and 6.8 kg day^{-1}; after the water was diverted (March 2011–February 2012, n = 13) the average Pb load was 1.4 kg day^{-1}, the range was between 0.1 kg day $^{-1}$ and 4.5 kg day^{-1}.

Prior to the diversion (July 2004–December 2007, n = 20) the average Zn load was 35.5 kg day^{-1}, the range was between 6.9 kg day $^{-1}$ and 106.1 kg day^{-1}; after the water was diverted (March 2011–February 2012, n = 13) the average Zn load was 26.5 kg day^{-1}, the range was between 2.0 kg day $^{-1}$ and 78.1 kg day^{-1}.

Figure 2.6 shows the flows and the metal loads at Frongoch Adit following the diversion of water from the portal to the Frongoch Stream from March 2011 to February 2012. Pb and Zn loads increase with the flow and there is limited dilution associated with a greater flow.

Table 2.1 Zn and Pb loads at the adit based on spot or continuous flow gauging

date	Pb load kg/day (spot flow gauging)	Zn load kg/day (spot flow gauging)	Pb load kg/day (cont flow gauging)	Zn load kg/day (cont flow gauging)
12/07/2004	0.72	16.15	0.72	16.15
04/08/2004	1.54	34.95	1.54	34.95
15/09/2004	6.84	106.12	6.84	106.12
10/11/2004	1.62	23.73	1.62	23.73
29/11/2004	1.87	29.65	1.87	29.65
07/12/2004	1.21	26.08	1.21	26.08
07/04/2005	1.65	26.38	1.65	26.38
20/04/2005	3.74	58.00	3.74	58.00
19/05/2005	0.62	11.79	0.62	11.79
27/02/2007	5.89	91.07	5.89	91.07
27/03/2007	2.44	37.23	2.44	37.23
24/04/2007	1.41	26.76	1.41	26.76
22/05/2007	1.00	16.01	1.00	16.01
26/06/2007	0.96	16.29	0.96	16.29
24/07/2007	3.96	45.80	3.96	45.80
21/08/2007	2.21	32.68	2.21	32.68
25/09/2007	3.00	43.03	3.00	43.03
18/10/2007	0.45	6.95	0.45	6.95
13/11/2007	0.90	13.84	0.90	13.84
11/12/2007	4.63	46.64	4.63	46.64
22/03/2011	0.12	2.00	2.82	47.07
14/04/2011	0.18	2.28	3.71	48.19
08/06/2011	0.30	3.58	0.30	3.58
15/07/2011	0.45	6.60	0.43	6.28
22/08/2011	0.26	4.04	0.26	4.04
09/09/2011	2.07	31.57	0.00	0.00
22/09/2011	1.66	30.23	8.19	148.80
13/10/2011	4.52	70.98	9.13	143.52
03/11/2011	1.28	26.74	9.36	195.59
11/12/2011	1.99	37.87	11.19	212.96
14/12/2011	3.48	78.15	10.68	239.76
11/01/2012	1.51	35.00	10.18	236.65
03/02/2012	0.74	15.16		

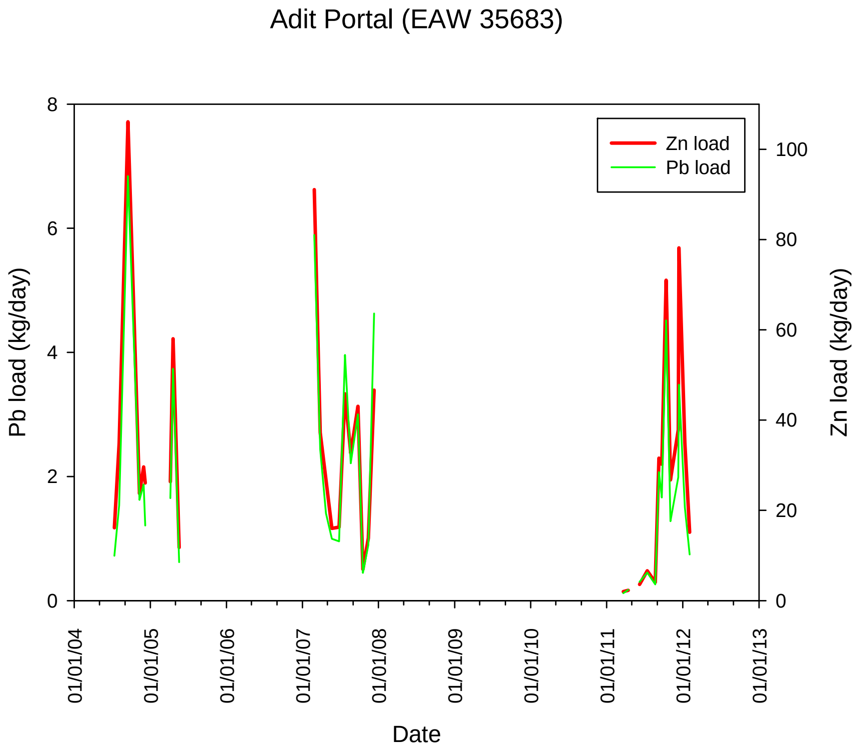


Figure 2.5 Zn and Pb load in the adit portal discharge, January 2004 to February 2012.

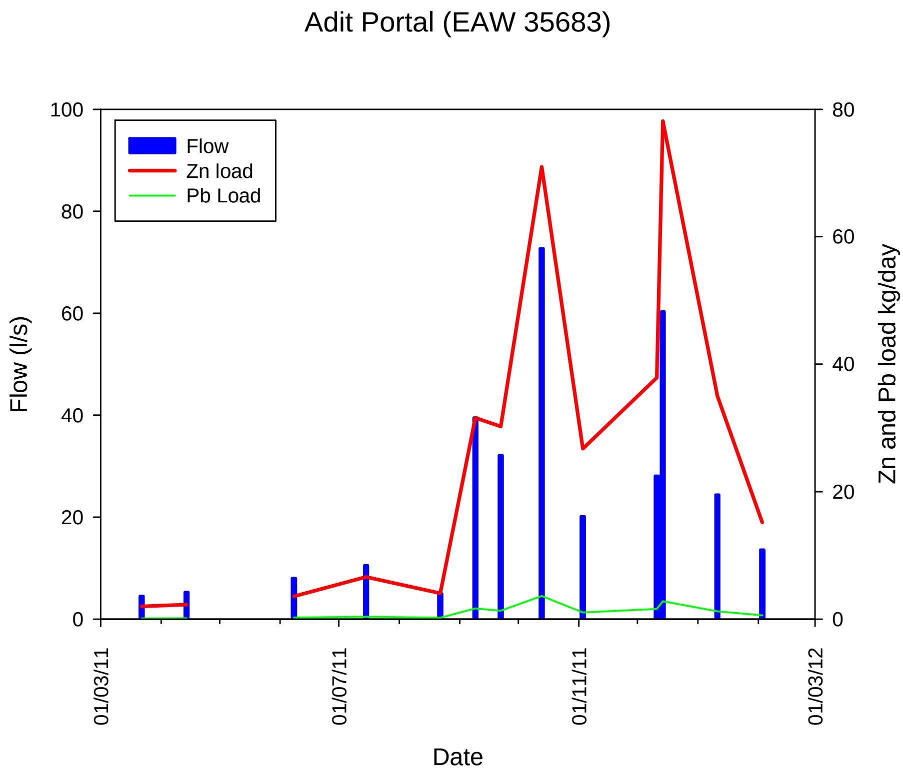


Figure 2.6 Zn and Pb load presented with flow measurements of the adit portal discharge, March 2011 to February 2012.

2.2 THE FRONGOCH STREAM D/S MINE (EAW 35690)

Monthly data were collected between July 2004 and July 2005. There was no sample taken in October 2004, but two samples were taken the following month, likewise there was no data for March 2005, but two samples were taken in April. Between January and December 2007 monthly data are available. Six data points are unevenly spaced between December 2008 and December 2009. From March 2001 to February 2012 samples are taken once or twice each month.

2.2.1 Pre- and post- stream diversion changes in flow

Figure 2.7 presents flow data for the Frongoch Stream. The average measured flow prior to the stream diversion (i.e. 2004-2008) was 17 l/s, whereas after the diversion the average flow was 62 l/s.

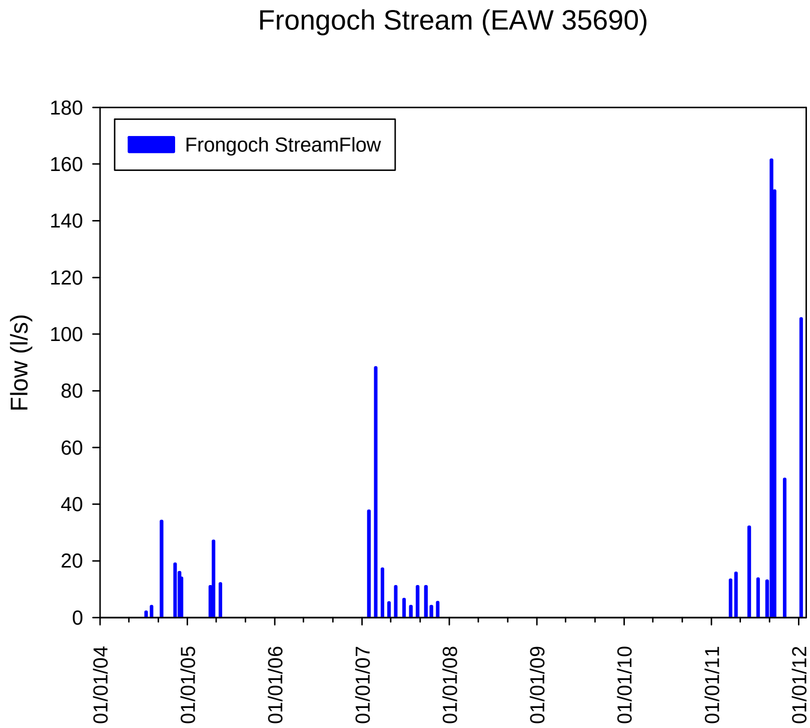


Figure 2.7 Flow measurements from the Frongoch Stream 2004 – 2012

2.2.2 Pre- and post-diversion changes in water quality

Figure 2.8 shows that Pb and Zn concentrations display similar trends, and were variable over time. The diversion of water into the stream has caused a large dilution and a significant improvement in water quality; the Pb concentration dropped from 1550 µg L^{-1} to 411 µg L^{-1}, and the Zn decreased from 19500 µg L^{-1} to 2960 µg L^{-1}. The concentrations remained fairly constant thereafter (Figure 2.9).

Comparison of the concentration and flow data on various dates (Figure 2.10) does not show a constant relationship between the two measurements, i.e. high stream flows do not always correspond to the lowest metal concentrations, as would be expected from dilution effects, but, likewise, high flows do not always correspond to high metal concentrations, as indicative of a significant dissolved metal contribution to the stream through surface runoff. It is likely that the reason for non-unique response between flow and concentrations is due to the influence of the antecedent rainfall regime preceding the sampling event, which affects the infiltration/runoff ratio and consequently the potential for leachable metals to be flushed out into the stream. This makes comparison of stream concentrations for similar flow conditions difficult.

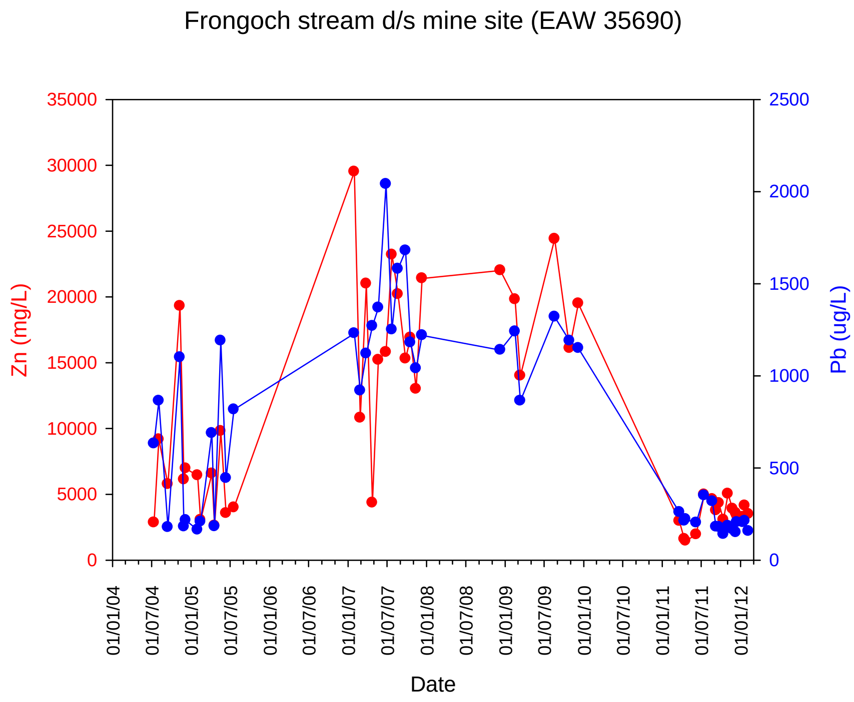


Figure 2.8 Pb and Zn concentrations in Frongoch Stream.

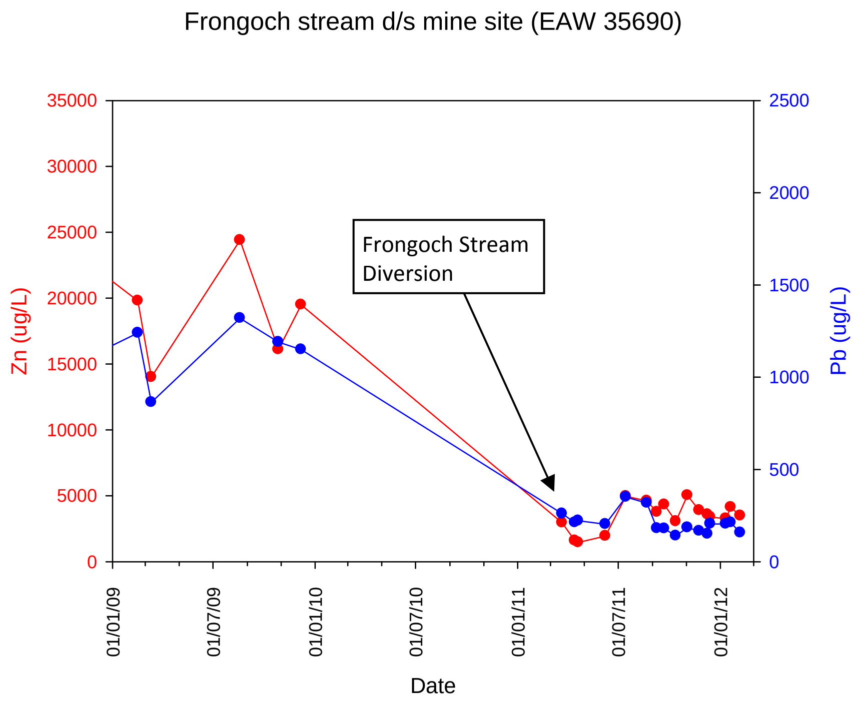


Figure 2.9 Pb and Zn in Frongoch Stream January 2009 to January 2012. The point at which the diversion took place is marked.

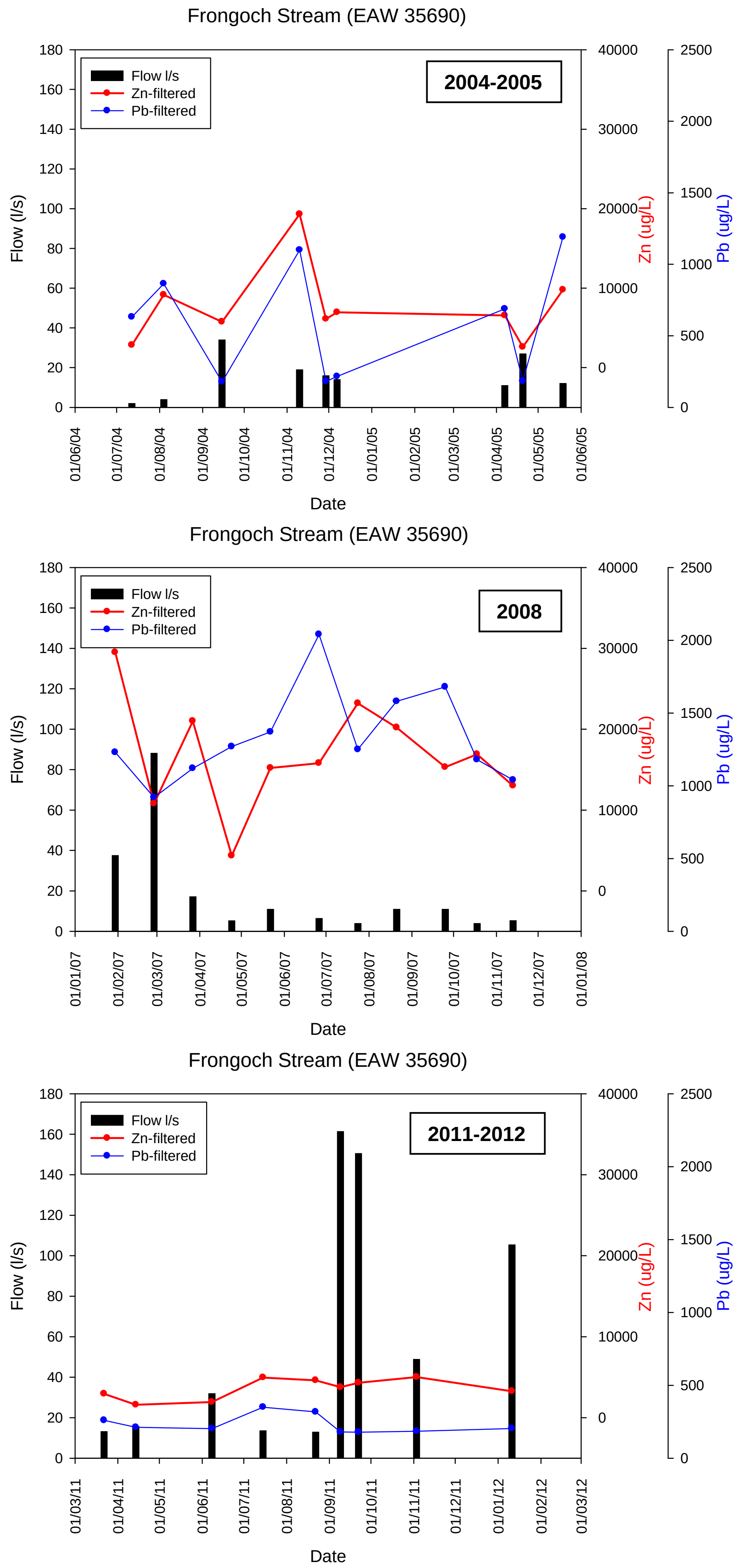


Figure 2.10 Concentrations of Zn and Pb presented with stream flow of the Frongoch Stream at varying monitoring times.

2.2.3 Pre- and post-diversion changes in metal loading

Figure 2.11 shows the loading of Pb and Zn in Frongoch Stream. The two elements follow a similar trend. Prior to the stream diversion (July 2004 – November 2007, n =20) the average Pb load was 1.28 kg day^{-1}, the range was between 0.11 kg day^{-1}, and 7.0 kg day^{-1}; after the water was diverted (March 2011 – January 2012, n= 9) the average Pb load was 1.0 kg day^{-1}, the range was between 0.28 kg day^{-1}, and 2.5 kg day^{-1}. Prior to the diversion (July 2004 – November 2007, n =20) the average Zn load was 19.0 kg day^{-1}, the range was between 0.49 kg day^{-1}, and 95.8 kg day^{-1}; after the water was diverted (March 2011 – January 2012, n= 9) the average Zn load was 20 kg day^{-1}, the range was between 2.2 kg day^{-1} and 56.2 kg day^{-1}. Figure 2.12 shows the loading with the flow data for the most recent period of monitoring, between March 2011 and January 2012, where the relationship between flow and loading is strong (Pb: r^2 = 0.99, Zn: r^2 =0.97). For this period the highest loading is generally present during peak flows.

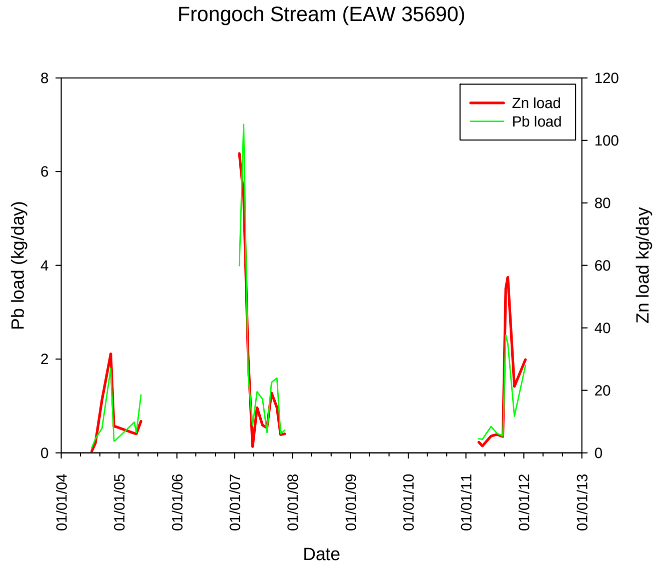


Figure 2.11 Zn and Pb load in the Frongoch Stream, January 2004 to January 2012.

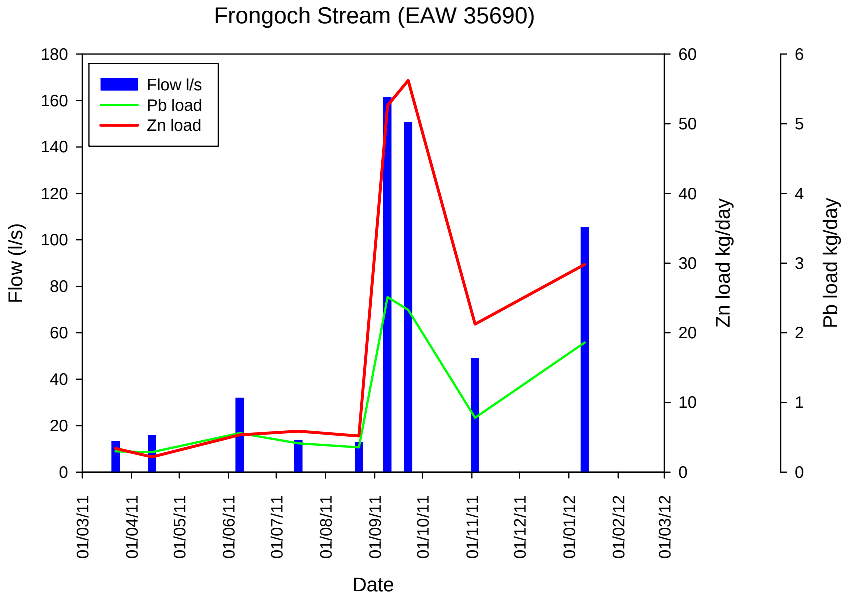


Figure 2.12 Zn and Pb load presented with flow measurements of the Frongoch Stream, March 2011 to January 2012.

2.3 CULVERT (EAW 35598)

The data set extends from March 2009 to February 2012. In 2009 samples were collected in March, October and December. From November 2010 to August 2011 most samples were collected monthly (however, there was no sample in February or May, and two samples in April 2011). From September 2011 samples are mostly collected twice every month. The water sampled at the culvert as well as the surface water sample (EAW 35600) are not influenced by the stream diversion remedial measure of March 2011.

2.3.1 Flow analysis

Figure 2.13 shows the flow issuing from the culvert. Where the flow was recorded at <1 l/s it is presented on the graph as 0.5 l/s. The flow issuing from the culvert is generally very low, ranging from <1 l/s to 5 l/s with an average of 2.11 l/s.

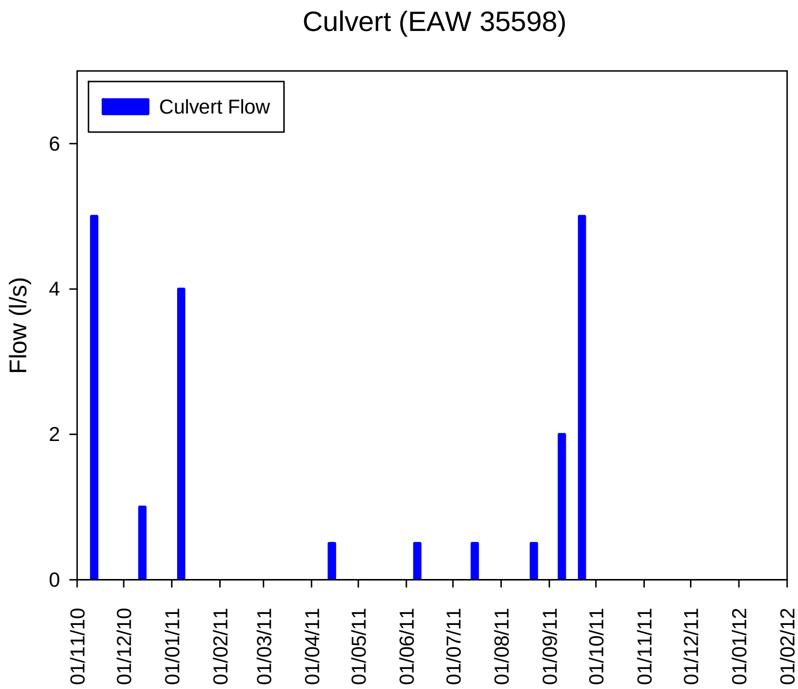


Figure 2.13 Flow measurements from the culvert.

2.3.2 Water quality

The concentrations of Pb and Zn in the culvert discharge are shown in Figure 2.14. The two elements respond similarly over time, except for one anomaly in the Zn data on the 12/11/2010.

During the monitoring period 2009 until February 2012 Zn concentrations ranged between 66700 μgL^{-1} to 239000 μgL^{-1} (average 94600 μgL^{-1}) and Pb concentrations range 1690μgL^{-1} and 8970 μgL^{-1} (average 3740 μgL^{-1}). Based on the available data, the winter months are on average the months with the lowest concentrations of both Zn and Pb, while the highest concentration peaks are recorded for Zn mostly in the summer months and for Pb in spring/summer. When comparing concentrations and flows the highest concentrations are associated with flows lower than 1 l/s.

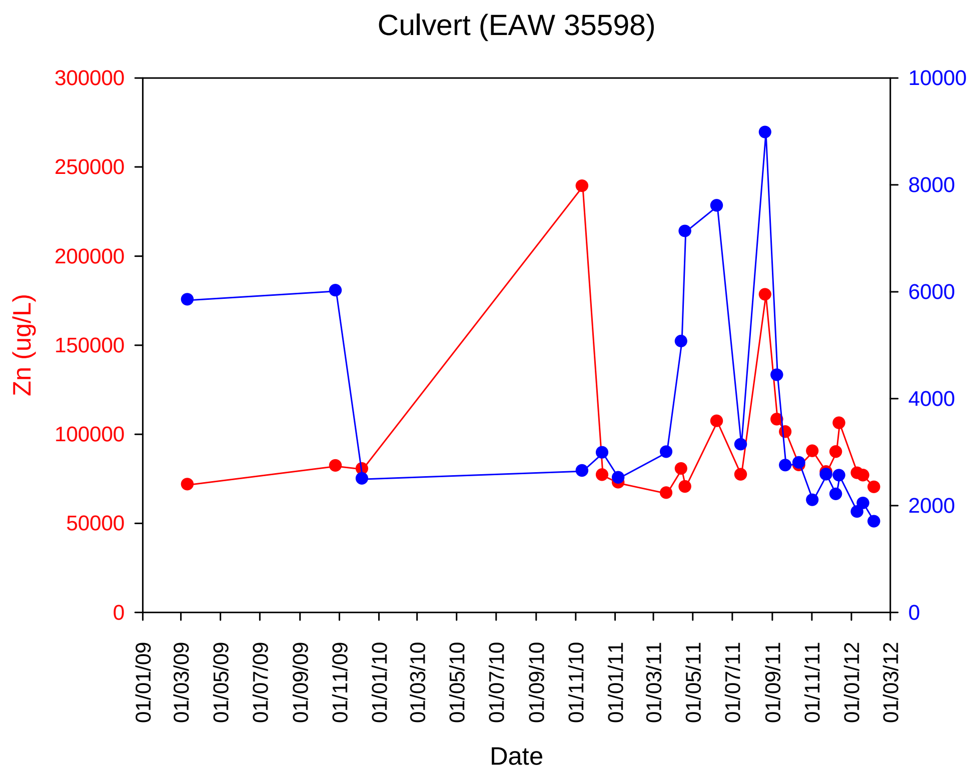


Figure 2.14 **Concentration of Pb and Zn in the water draining from the culvert.**

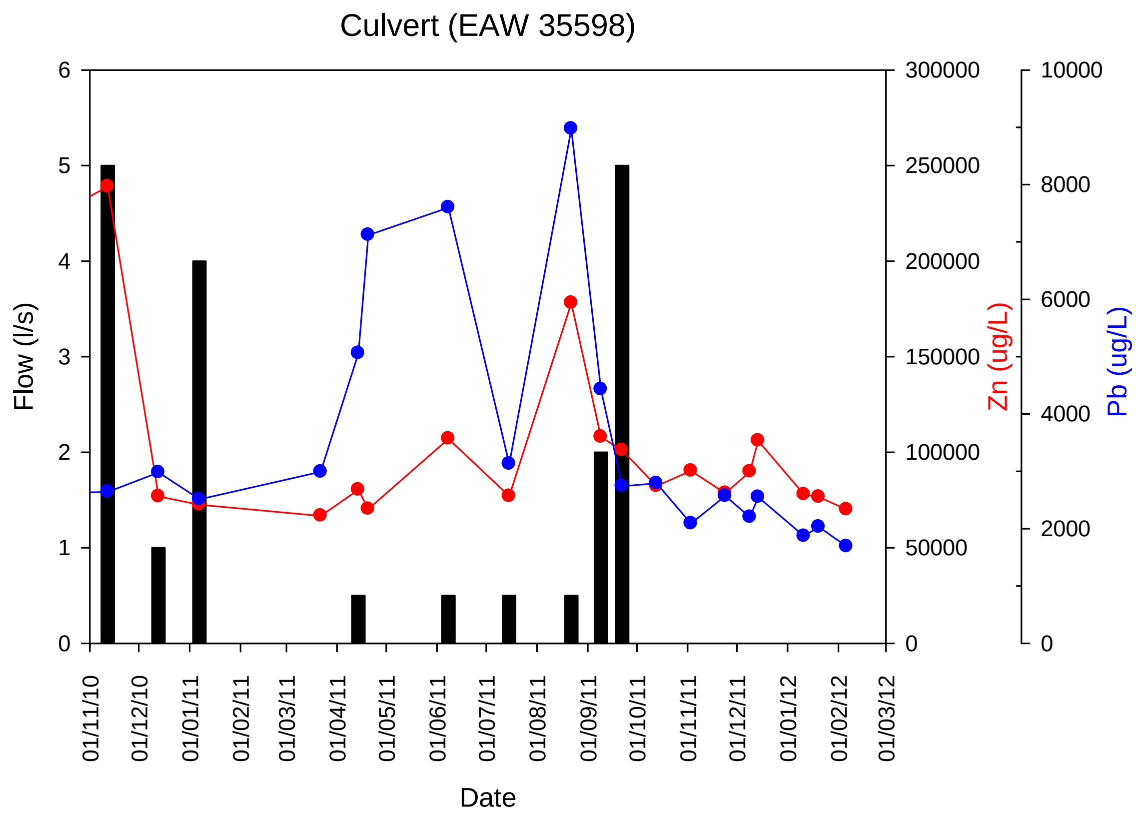


Figure 2.15 **Concentration of Pb and Zn against flow in the culvert drainage.**

2.3.3 Metal loads

Figure 2.16 shows the Pb and Zn load discharged from the culvert, presented with the flow measurements. The two elements follow a similar trend. Between November 2010 and September 2011 the average Pb load was 0.59 kg day^{-1}, and it ranged between 0.13 and 0.12 kg day^{-1}. The average Zn load was 24 kg day^{-1}, and it ranged between 3.3 and 103 kg day^{-1}. The loading was generally highest in the winter months and corresponds to the highest flow. There is a strong relationship between metal load and flow (Pb r^2=0.92, Zn r^2=0.94 with one outlier removed).

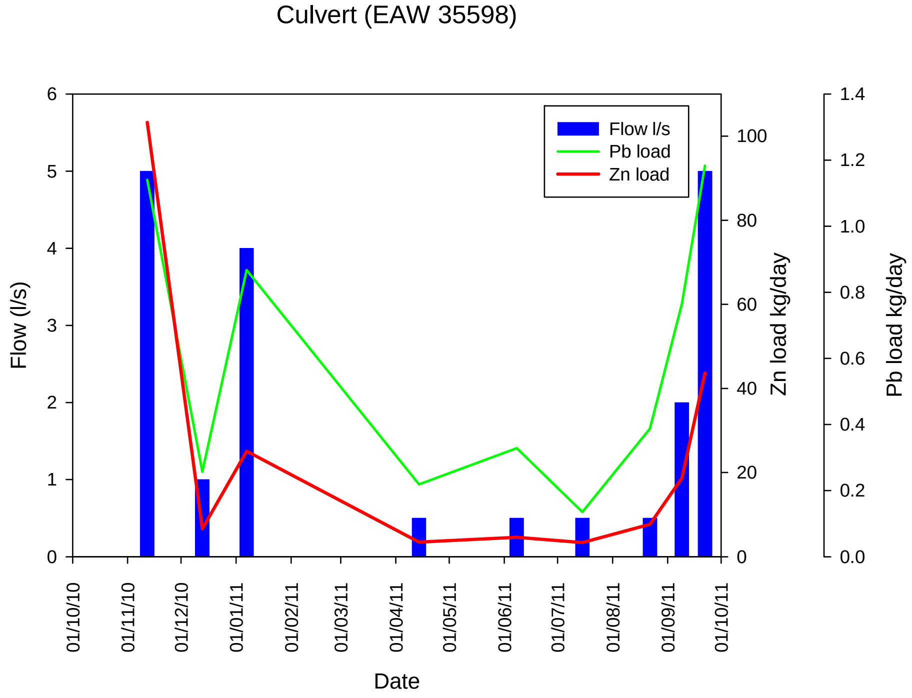


Figure 2.16 Zn and Pb load presented with flow measurements of the culvert discharge, November 2010 to September 2011.

2.4 SURFACE WATER SAMPLE (EAW 35600)

The data set extends from June 2011 to February 2012. An additional sampling point is December 2009. The concentration trends for Zn and Pb over the monitoring period are shown in Figure 2.17. Zn concentrations ranged between 1400 μgL^{-1} and 328000 μgL^{-1} (average 11800 μgL^{-1}) and Pb concentrations ranged between 2490 μgL^{-1} and 5710 μgL^{-1} (average 4150 μgL^{-1}).

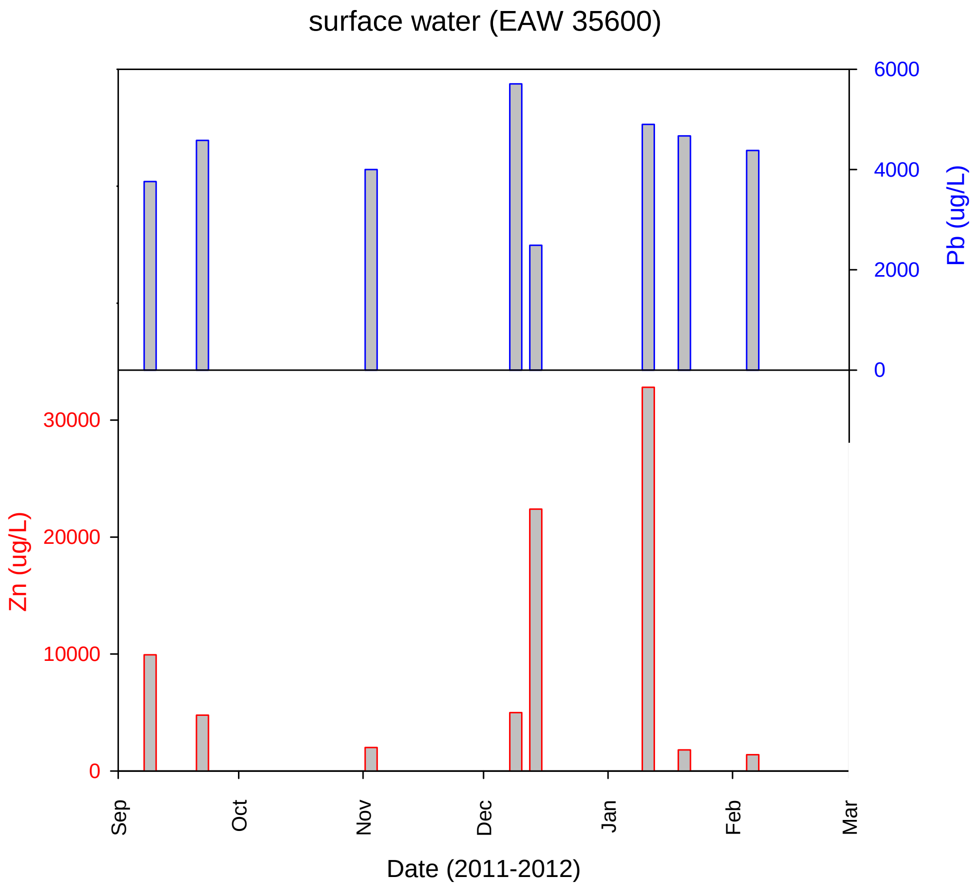


Figure 2.17 Concentrations of Pb and Zn in surface water from the tailings.

3 Discharge and rainfall

3.1 ADIT FLOW AND RAINFALL COMPARISON

Figure 3.1 displays the spot flow and daily rainfall data for the period between January 2007 and January 2008. During this period the spot flow data ranged from 13 to 310 l/s, and the average flow was 94 l/s. The highest flows presented on this graph (310 l/s recorded on 22/2/2007 and 214 l/s recorded on 11/12/2007) occurred after sustained moderate quantities of rainfall, rather than a single large event (68.4 mm recorded in the fortnight prior to the measurement on 22/2/12 and 134.4 mm recorded in the fortnight prior to the measurement on 11/12/2007). In comparison, the lowest flow of 13 l/s was recorded on 18/10/12 after only 29 mm of rain fell in the preceding fortnight, and only 14 mm of this volume fell in the week preceding the flow measurement.

A previous assessment of the daily gauged flow and rainfall data undertaken by Atkins for the same period indicated a rapid response to rainfall at the Frongoch Adit, with flow peaks appearing 1-2 days after a storm event and dropping off rapidly thereafter. A scenario of an open mine system with high temporary storage but limited baseflow from deeper groundwater was suggested. It was also noted that a sustained period of rainfall in Nov-Dec 2007 was causing the mill pond to overflow maintaining significant baseflow.

Figure 3.2 displays the spot flow measurements plotted against daily rainfall data from February 2011 to February 2012. During this period the flow ranged from 4.5 to 72 l/s, and the average flow was 25 l/s. Figure 3.2 clearly shows that flow issuing from the Frongoch Adit correlates with the rainfall. Where there is little or no rainfall in the days preceding the monthly flow measurement the flow is low. For example the flow on the 22nd March 2011 was 4.5 l/s, which corresponded to rainfall in the previous week of 0.6mm and the flow measured on 8th June 2011 was 8 l/s, and in the previous week there had only been 10 mm of rainfall. Where there was high rainfall in the days preceding the monthly flow measurement the flow is high. For example, the highest flow was recorded on 13th October 2011 (73 l/s) and in the preceding week there was 39 mm of rainfall.

In addition to the spot measurements of flow, since 7/2/11, the EA have recorded the daily mean flow of the adit discharge (Figure 3.3 and Figure 3.4). From 7/2/2011 to 30/1/2012 flow ranges from 106 to 249 l/s with December, January and February being the months with the highest flow values. The average flow was 142 l/s.

Figure 3.4 shows the period between September 2011 and January 2012. During this period, the flow ranged from 132 to 199 l/s and the average flow was 154 l/s. Clear increases in flow rate can be seen shortly after heavy rainfall. For example, on 18/10/11 there was 14.8 mm of rainfall, followed on 19/10/11 with a peak flow of 159 l/s. The response to rainfall is ‘flashy’ with flow rising quickly and then subsiding more gradually.

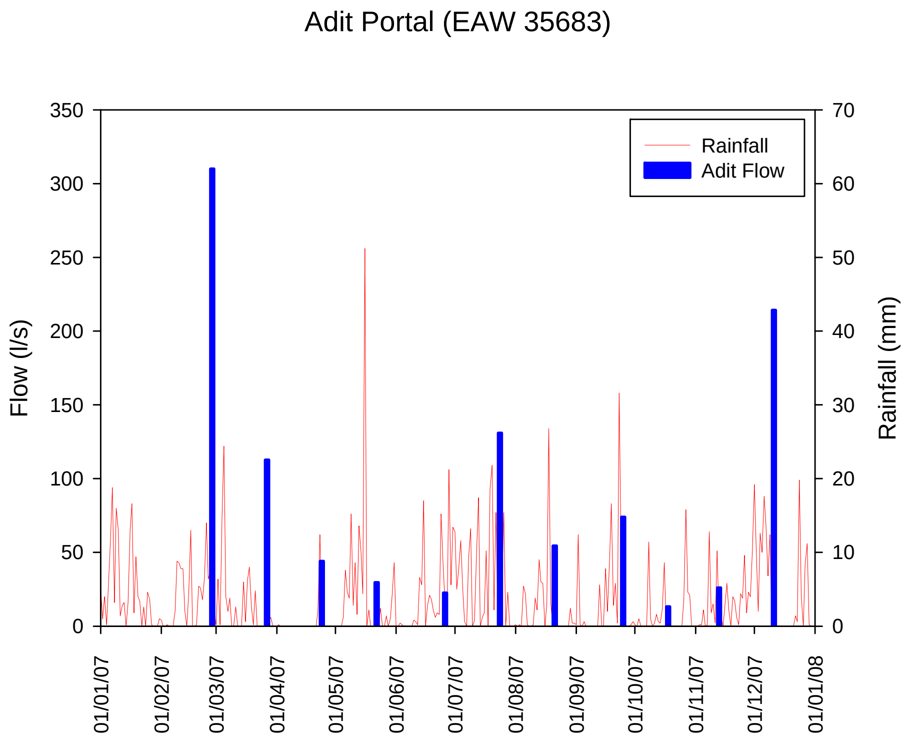


Figure 3.1 Flow and rainfall measurements from the Frongoch Adit, January 2007 – January 2008.

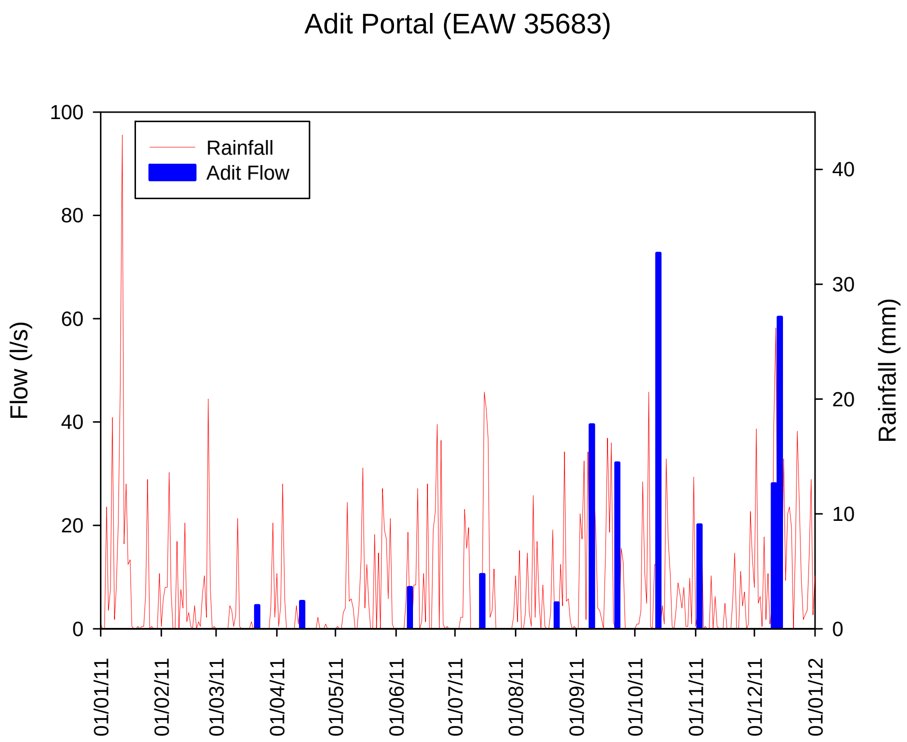


Figure 3.2 Spot Flow and rainfall measurements from the Frongoch Adit, February 2011 – February 2012.

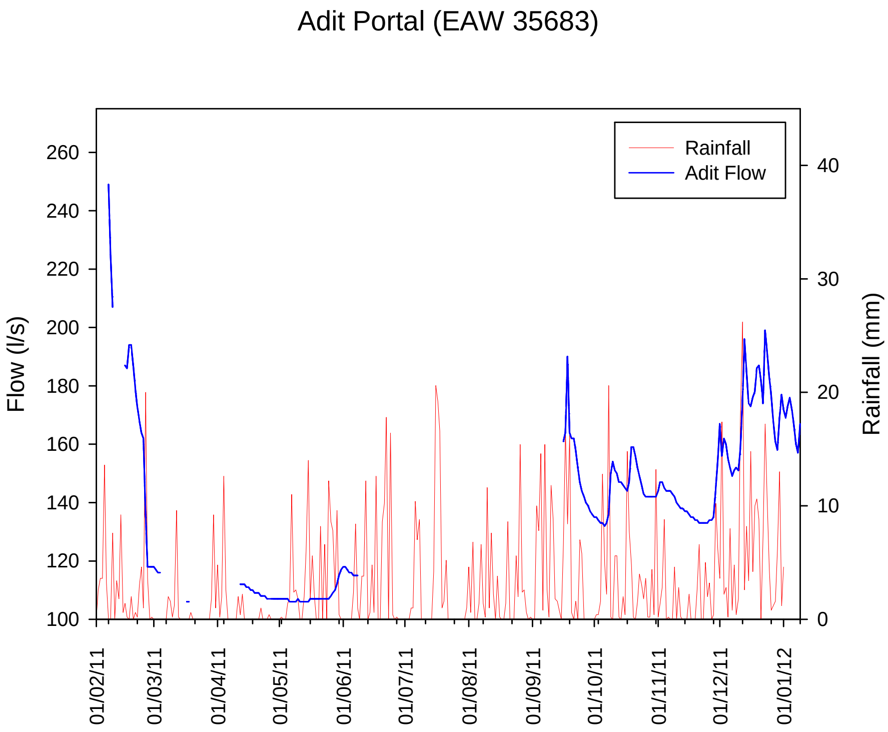


Figure 3.3 Daily mean flow at Frongoch Adit with corresponding rainfall data, January 2011 – February 2012.

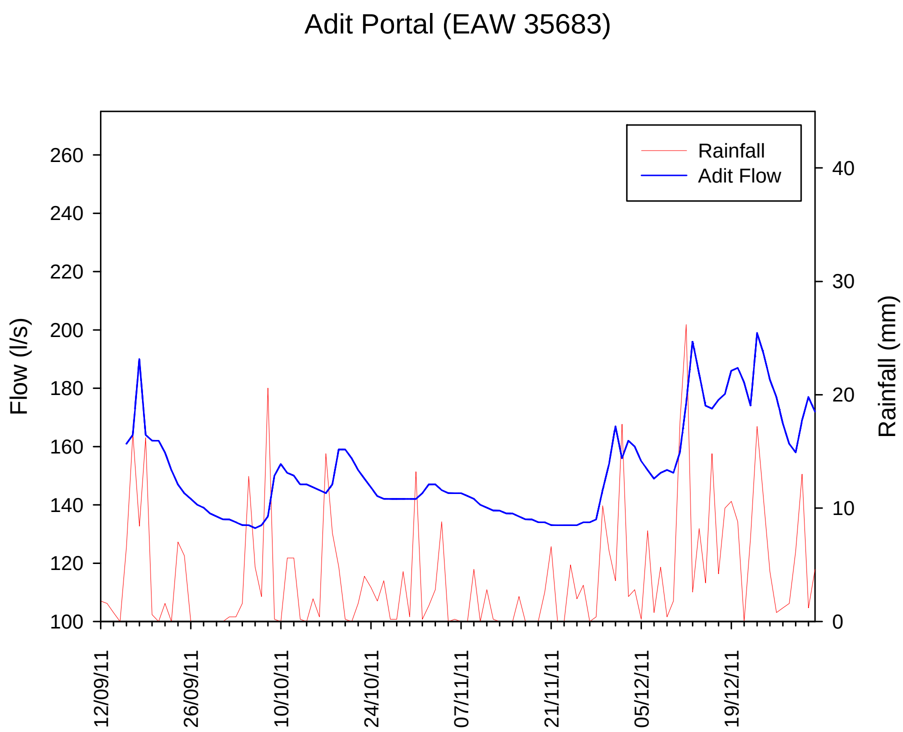


Figure 3.4 Daily mean flow at Frongoch Adit with corresponding rainfall data, September 2011 – December 2011.

3.2 FRONGOCH STREAM FLOW AND RAINFALL COMPARISON

Figure 3.5 displays flow in the Frongoch Stream and corresponding rainfall data for the period between January 2007 and January 2008. The flow ranged from 4 to 88 l/s, and the average flow was 18 l/s. The stream does not appear to respond to rainfall events; although this may be a function of the sampling frequency. The stream currently receives the diverted water from the Frongoch pond overflow as well as overland flow from the surrounding hillside. This means that if the pond is not full the stream would not necessarily receive the diverted water. The largest flow events may represent the overflow from the pond, rather than direct response to rainfall.

Figure 3.6 displays flow in the Frongoch Stream and the corresponding rainfall data for the period between January 2011 and January 2012. The flow ranged from 13 to 161 l/s and the average flow was 62 l/s. These data represent measurements of flow taken after the stream diversion; hence, the flow values are much greater than those measured prior to the engineering works. There were two very high flow measurements, despite the rainfall being average in the previous weeks. If the flow data were more frequent, a correlation may be evident.

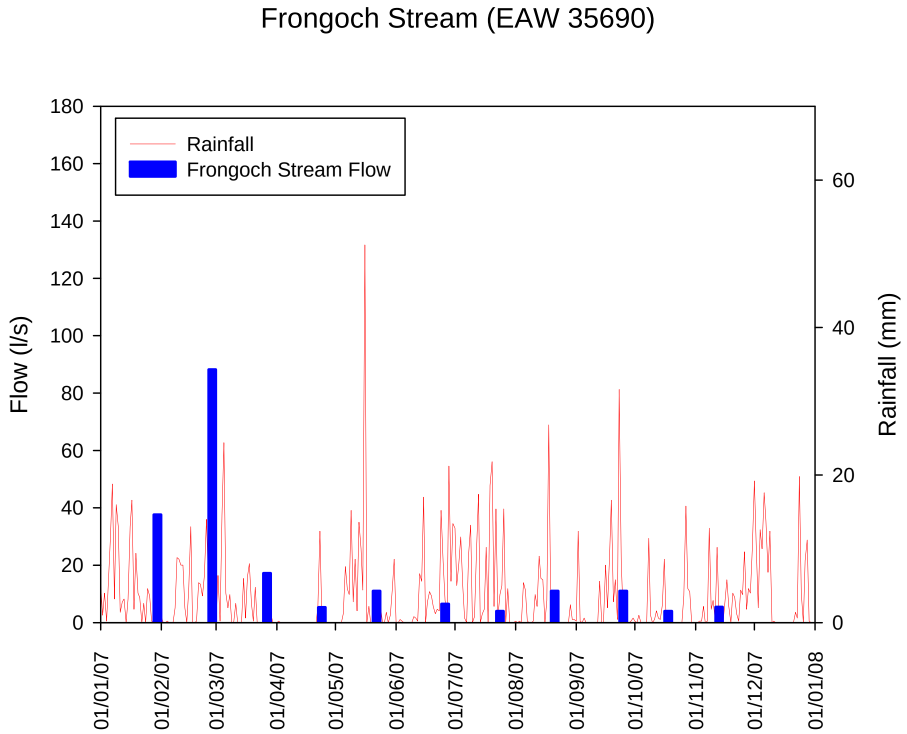


Figure 3.5 Flow and rainfall measurements from the Frongoch Stream, January 2007 – January 2008

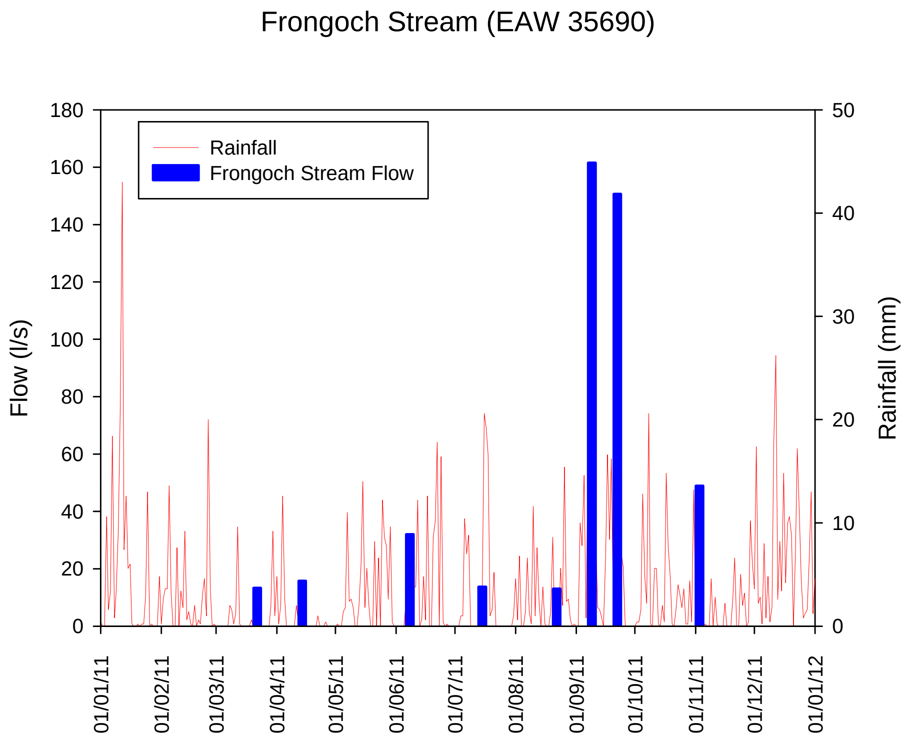
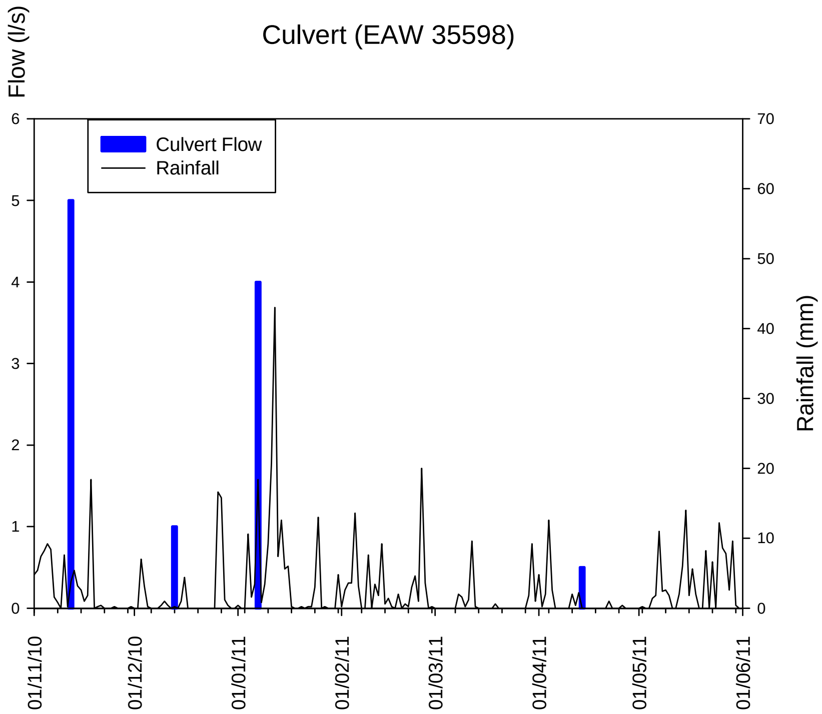


Figure 3.6 Flow and rainfall measurements from the Frongoch Stream, January 2011 – January 2012.

3.3 CULVERT FLOW AND RAINFALL COMPARISON

Figure 3.7 shows that discharge at the culvert can peak in response to rain events. Previous single borehole dilution tests (Maurice et al. 2012) indicated a low groundwater velocity of ~ 0.4 m/d in the tailings around borehole BH3. However, it is possible that a proportion of water in the spoils moves relatively quickly through preferential flow and could account for the hydrograph response to rainfall. This is favoured during wet conditions. Another explanation would be the piston effect, i.e. the head transmission through the aquifer can cause displacement of stored water. However, the lower metal concentrations at the culvert discharge on those high flow events seem to support the hypothesis of preferential flow, rather than piston flow. A flow at the culvert, although very low (< 1 l/s) is noticed in dry periods (e.g. April 2011) suggesting a matrix flow moving relatively slowly through the waste.



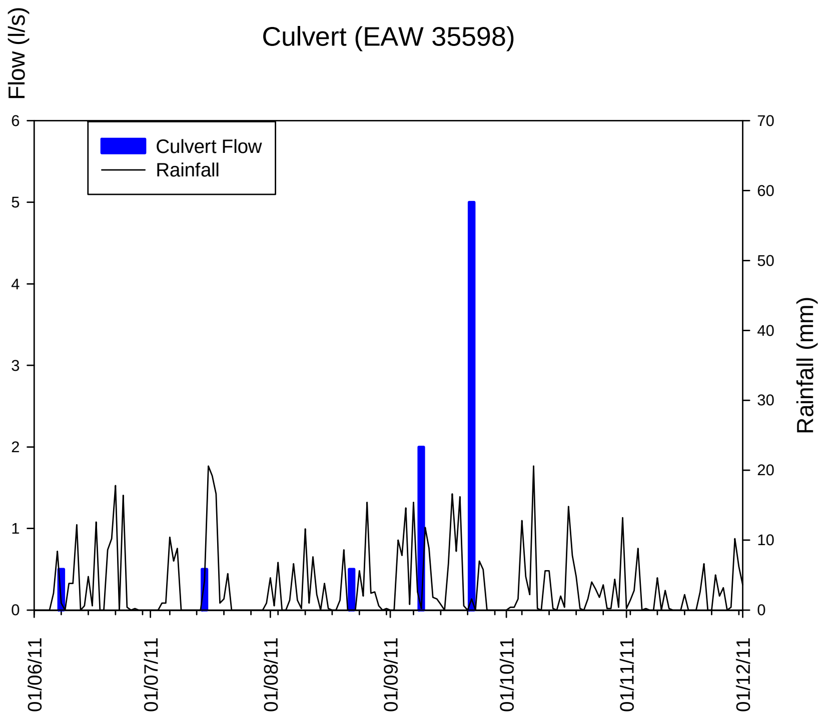


Figure 3.7 Flow and rainfall measurements from the Culvert, June 2010 – February 2012.

4 BGS groundwater data analysis

Figure 4.1 summarises the BGS analysis of Zn and Pb concentrations in the waters sampled at the mine site, including the groundwater from the two boreholes BH1 and BH3. These data have been discussed in detail in previous BGS reports (Palumbo-Roe et al. 2009 and Bearcock et al. 2010). Some further observations can be made in the attempt to discern potential water flow paths.

Groundwater from borehole BH1, the deeper borehole in the underlying clayey till, is consistently lower in Pb and similar or lower in Zn concentrations than BH3. Borehole 1's chemistry shows low seasonality for Zn, while the Pb content is higher in the sampling events corresponding to the cold months (March). It has been previously suggested that those metal concentrations in the deep borehole BH1 are evidence of the contaminated plume infiltrating down the tailings through the peat layer to the underlying glacial till. The higher Pb contents of the groundwater sampled in March are consistent with a higher infiltration during the winter months. The more significant enrichment in Pb rather than Zn in the winter months might be related to the strong binding capacity for Pb of the organic layer. The peat layer may act as a temporary sink for the metal, able to release it in response to moisture content changes. Despite the plausibility of the infiltration model an alternative hypothesis of a different source for this water cannot be completely be discounted.

By contrast, groundwater from borehole BH3, the shallow borehole intercepting the perched water in the mine tailings and peat layers, is enriched in Pb compared to BH1 and shows a significant seasonal trend in Zn concentration with much higher Zn in the warm sampling months. The seasonal change in groundwater chemistry is likely related to more significant evaporation from the spoil surface during the warm months and resulting enrichments in solution of soluble salts, which are readily dissolved in solution during recharge events.

It is important to note that the culvert discharge has relatively lower Zn concentrations than the groundwater in the boreholes and similar concentrations of Pb to the groundwater in BH3 and to the surface runoff. Based purely on the Pb concentrations, it would appear that the perched groundwater represented in BH3 drains into the culvert, while hydrological connectivity between BH1 and the culvert is less probable. However, the distinct Zn enrichment in BH3 in the July sample was only marginally evident in the culvert seepage on one of the sampling events. The lack of coincidence in peak contaminant concentrations may suggest long residence time or perhaps preferential subsurface flows in the spoils.

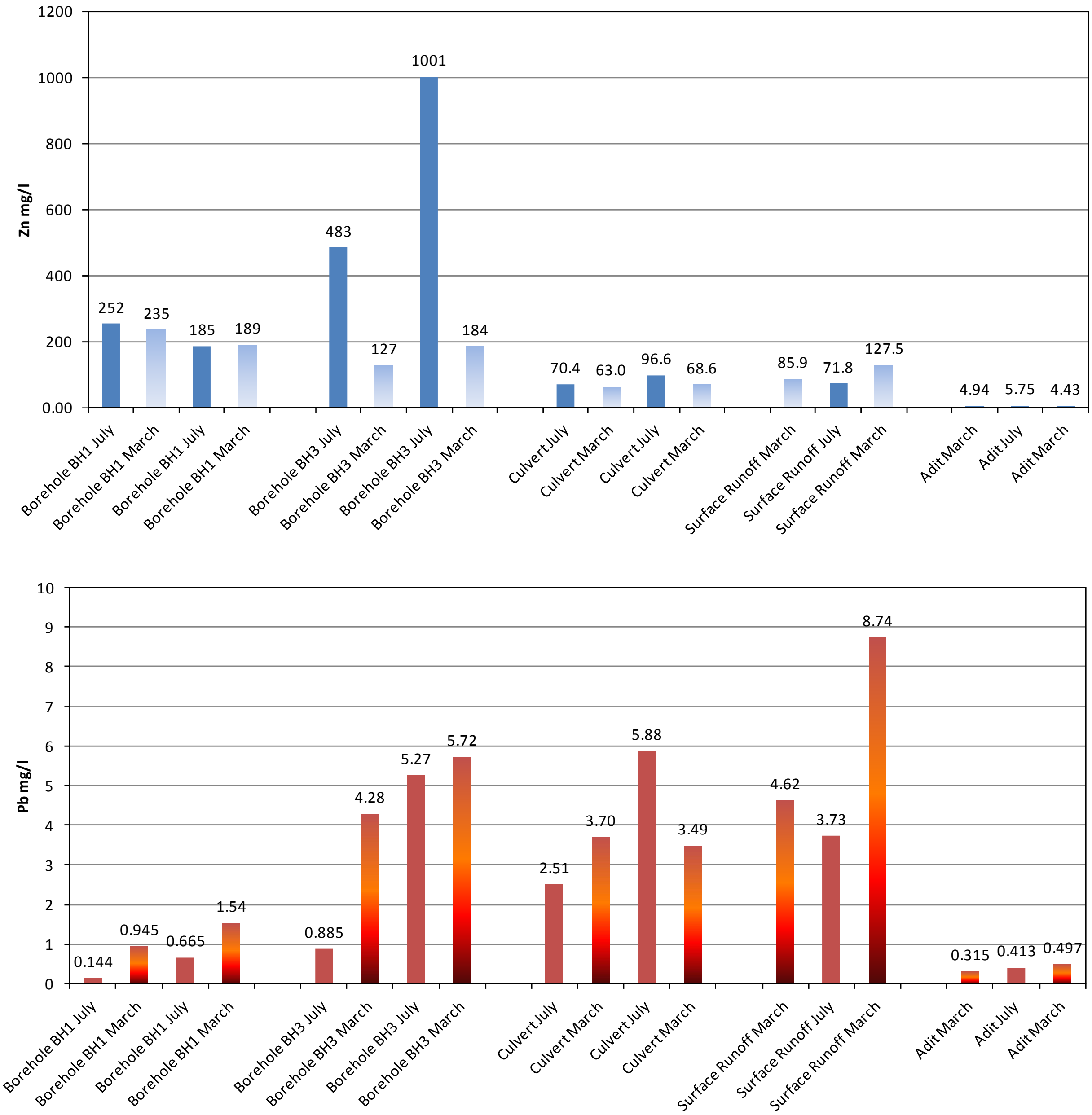


Figure 4.1 Plots of Zn and Pb concentrations in BGS water samples (data in Bearcock et al. 2010).

5 Mass balance –Nant Cell catchment

5.1 BGS SYNOPTING SAMPLING – NOVEMBER 2006 DATA

A mass balance for the Zn and Pb loadings in the Nant Cell has been calculated based on BGS unpublished data for quantifying source loading and in-stream processes. The synoptic sampling was carried out on the 13/11/2006 in the two sub-catchments of the Afon Ystwyth, affected by Frongoch Mine and Frongoch Adit, respectively, the Nant Cell and the Nant Cwmnewydion/Nant Magwr (Table 5.1 and Figure 5.1). The sampling points were selected in order to cover water stretches upstream and downstream of mine water discharges or at the confluence of major tributaries. Some of the sampling points were located in headwaters (Frongoch lake and small reservoir on east of the above lake) to monitor background concentrations.

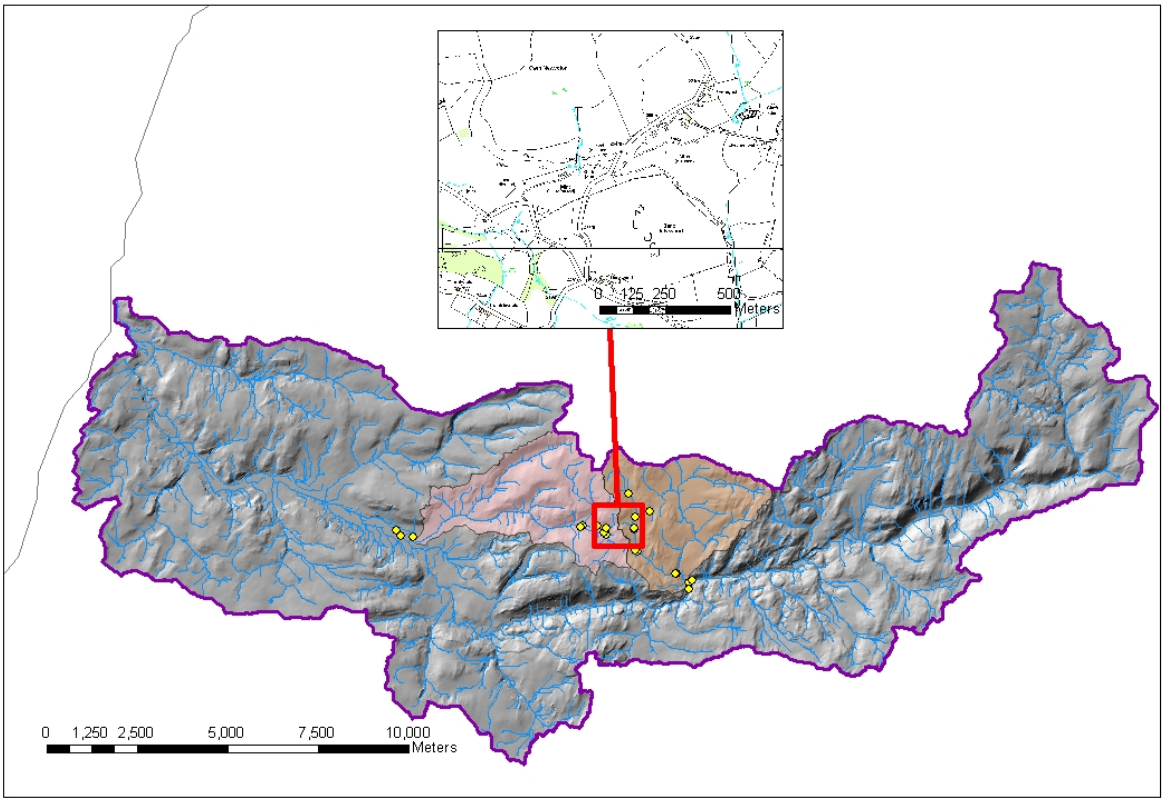


Figure 5.1 DTM image of the the Afon Ystwyth catchment with the two subcatchments affected by Frongoch Mine and Frongoch Adit highlighted: the Nant Cell (in brown) and the Nant Cwmnewydion/Nant Magwr (in pink) and a closer view of the Frongoch site topographic map. The yellow circles represent the monitoring points of the synoptic sampling carried out on the 13/11/2006 (NEXTMap Britain elevation data from Intermap Technologies).

The Pb and Zn concentrations with flow measurements and the Zn and Pb load profiles for the Nant Cell catchment are presented graphically in Figure 5.3, Figure 5.4, Figure 5.5. There are six points downstream of the mine site, extending to the confluence of the Nant Cell and the Ystwyth, plus points 1, 2 and 3 representing background concentrations upstream the mine site.

The Zn load profile (Figure 5.4) shows a decrease from point 4 to 5, suggesting a possible attenuation of the metal, while there is a large increase in Pb and Zn loads from point 5 to 6, due to the substantial increase of flow, but unvarying concentrations. This suggests a contribution of water enriched in both Pb and Zn metals between point 5 and 6. The "Frongoch & Wemysss Mine Site Monitoring Summary" Report by Atkins (2008) had highlighted the increased discharge due to a marsh area, but not in terms of increased load. The marsh area seems to act as a contaminant store, its capacity and residence time remains unknown until further investigation can be undertaken. While Zn concentration decreased downstream of location 6, the Zn load in the Nant Cell remained constant, suggesting very little attenuation by precipitation/sorption, with decreased concentrations due only to dilution. Differently from the Zn loadings, an increase in Pb load between site 10 to site 8 is observed.

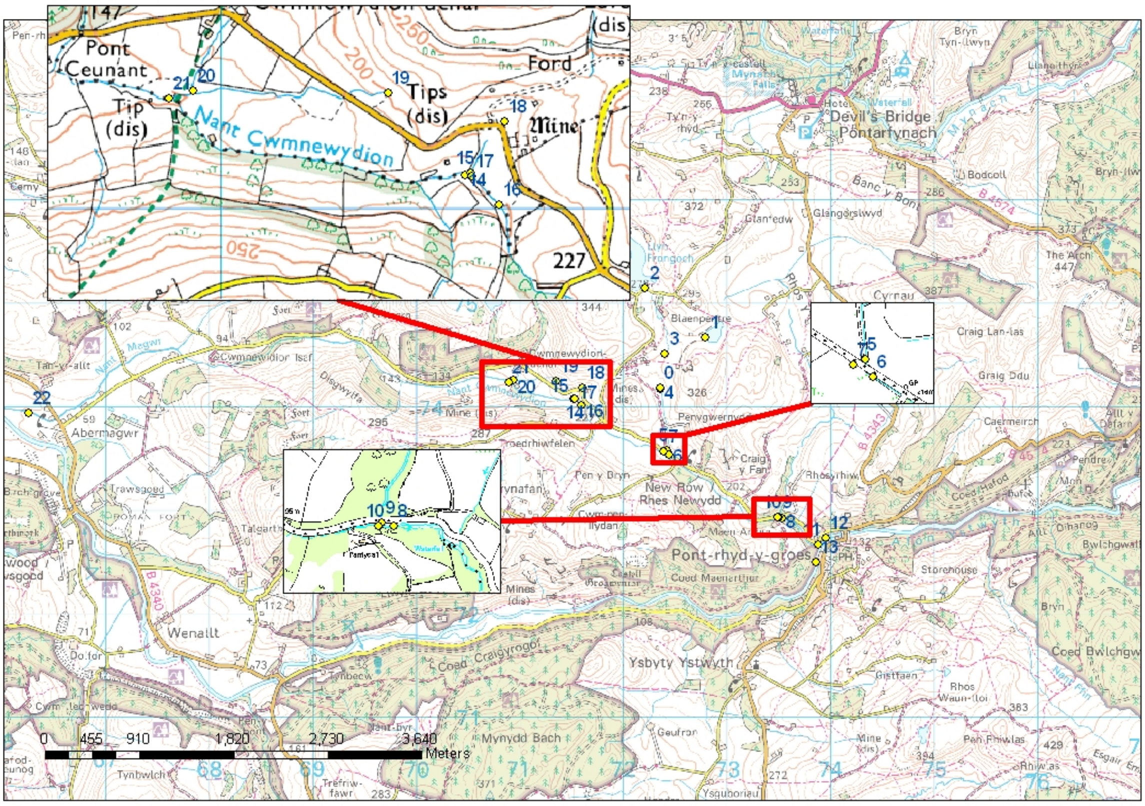


Figure 5.2 BGS sampling points of synoptic sampling carried out in November 2006.

Table 5.1 The location of synoptic sampling points (November 2006)

Location	Date	Easting	Northing	Description
1	13/11/2006	272795	274667	Outlet from unnamed mill pond u/s Frongoch Mine.
2	13/11/2006	272209	275151	Outlet from Llyn Frongoch.
3	13/11/2006	272402	274515	Waterfall into Frongoch Mine stope.
4	13/11/2006	272354	274173	Culvert below Frongoch tailings, at entry to perimeter ditch.
5	14/11/2006	272420	273579	Frongoch Stream (in ditch), d/s Frongoch site.
6	14/11/2006	272439	273533	Unnamed tributary of the Nant Cell, d/s confluence with Frongoch Stream.
7	14/11/2006	272388	273565	Unnamed tributary of the Nant Cell, u/s confluence with Frongoch Stream.
8	14/11/2006	273529	272925	Nant Cell d/s tributary impacted by Frongoch Mine.
9	14/11/2006	273500	272933	Nant Cell u/s tributary impacted by Frongoch Mine.
10	14/11/2006	273493	272927	Tributary to Nant Cell impacted by Frongoch Stream.
11	14/11/2006	273878	272667	Nant Cell before confluence to the Ystwyth.
12	14/11/2006	273958	272728	River Ystwyth upstream of Nant Cell.
13	14/11/2006	273865	272499	River Ystwyth downstream of Nant Cell.
14	14/11/2006	271516	274073	Nant Cwmnewydion d/s confluence with stream from Wemyss spoils.
15	14/11/2006	271529	274077	Unnamed stream from Wemyss spoils, before joining Nant Cwmnewydion.
16	14/11/2006	271590	274010	Nant Cwmnewydion u/s confluence with stream from Wemyss spoils.
17	14/11/2006	271530	274071	Nant Cwmnewydion immediately u/s confluence with stream from Wemyss spoils (d/s point 16).
18	14/11/2006	271601	274186	Drainage from Wemyss, immediately u/s road culvert.
19	14/11/2006	271353	274247	Frongoch Adit.
20	14/11/2006	270941	274251	Nant Gwyn, tributary of the Nant Cwmnewydion.
21	14/11/2006	270889	274234	Nant Cwmnewydion d/s of Nant Gwyn and d/s Frongoch Adit.
22	14/11/2006	266256	273935	Nant Magwr.
23	14/11/2006	265788	274124	River Ystwyth d/s Nant Magwr.
24	14/11/2006	265913	273985	River Ystwyth u/s Nant Magwr.

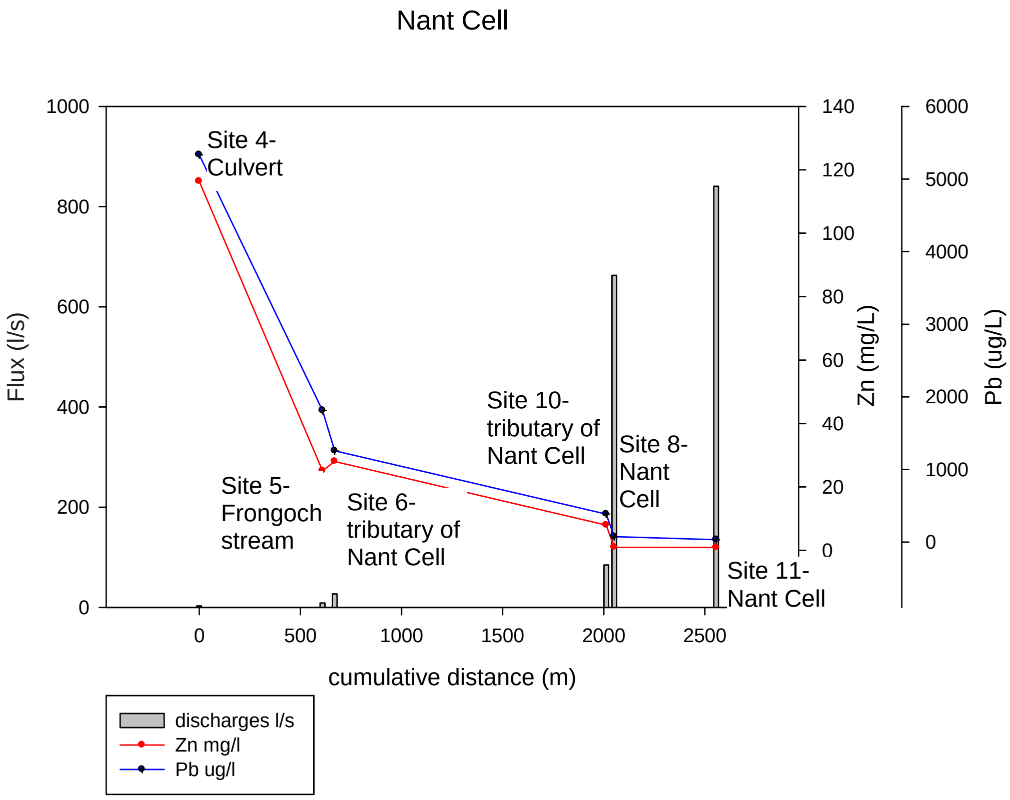


Figure 5.3 Fluxes and concentrations of Pb and Zn measured in the Nant Cell catchment.

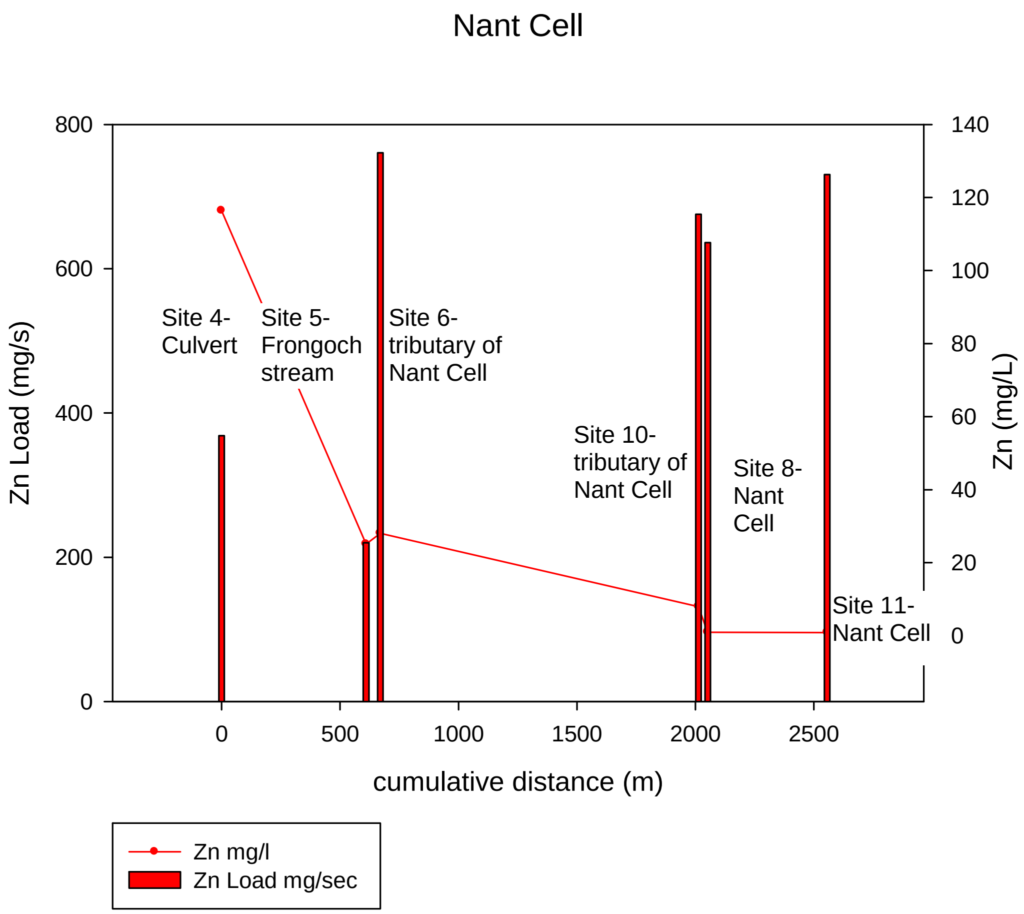


Figure 5.4 Zn concentrations and loads in the Nant Cell catchment.

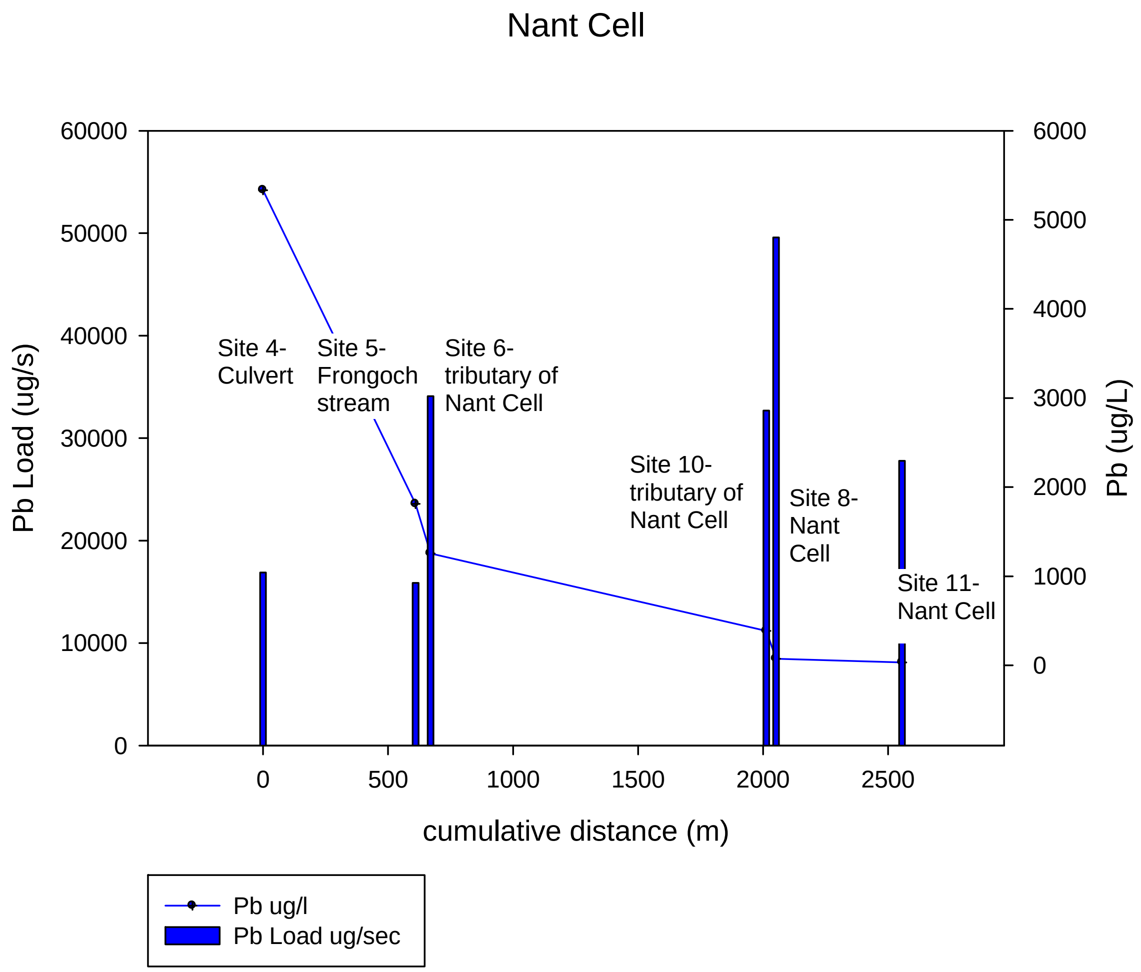


Figure 5.5 Pb concentrations and loads in the Nant Cell catchment.

5.2 EA DATA

The recent data collected by the EA(Wales) in the Nant Cell in 2011 confirm some of the above observed trends. The Zn and Pb concentration profiles along the Nant Cell at various sampling dates are shown in Figure 5.6.

It is noticeable that the Zn concentration of the Frongoch Stream at the downstream point 35591 does not increase despite the probable increase in flow of the Frongoch Stream at this point (flow data not available, but the stretch has been previously recognised as an area of recharge) (Figure 5.6).

The “surface water” samples over the tailings are significantly higher in Pb, while lower in Zn compared to the water discharging from the culvert. It is unclear the reason for this enrichment in Pb.

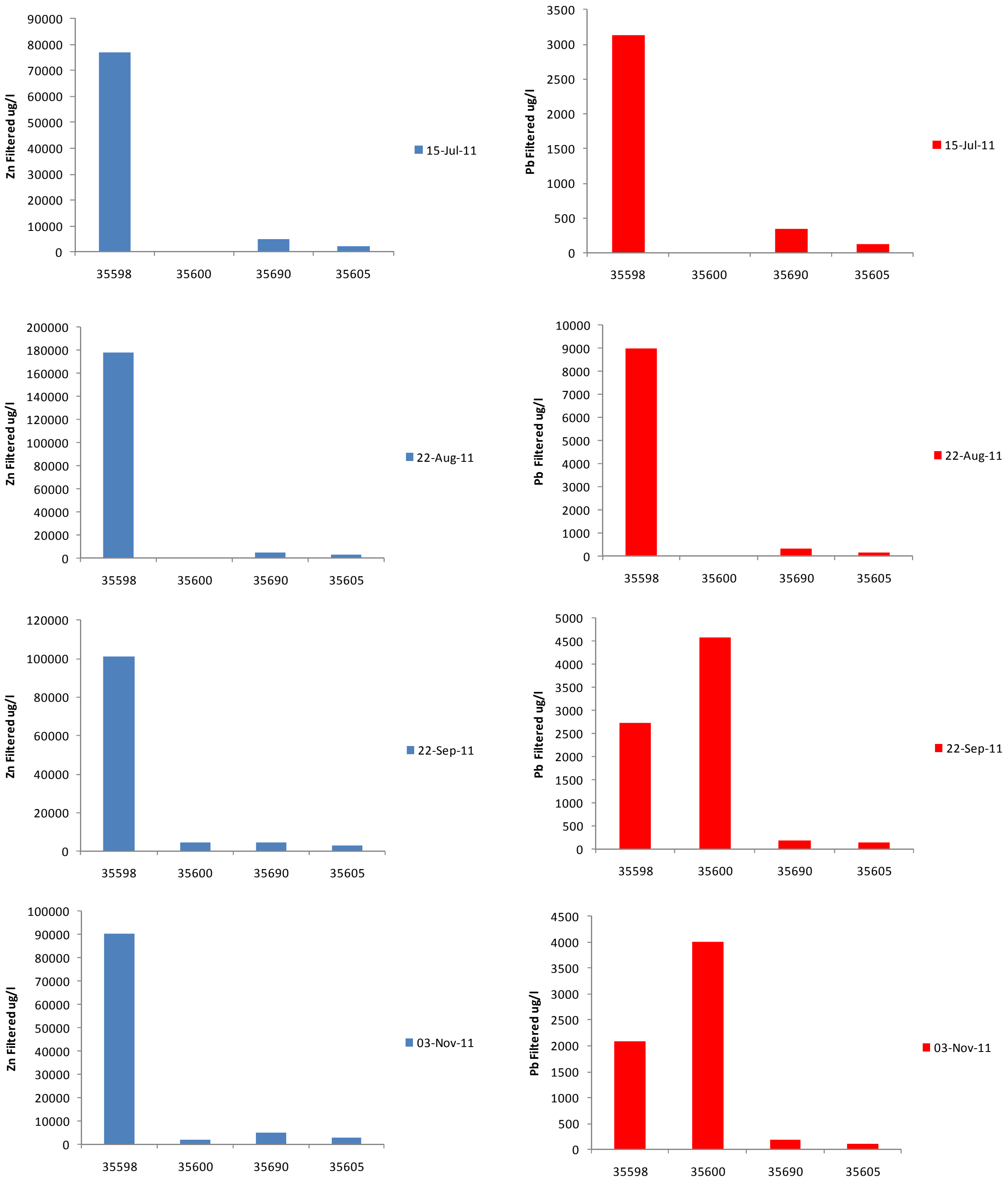


Figure 5.6 Zn and Pb concentration profiles along the EA monitoring sites in Nant Cell (site ID 35598: culvert; 35600: surface water over tailings; 35690: Frongoch Stream at gauge board; 35591: Frongoch Stream at road culvert; 35605 Frongoch Stream above confluence with Nant Cell; also refer to Table 1.1).

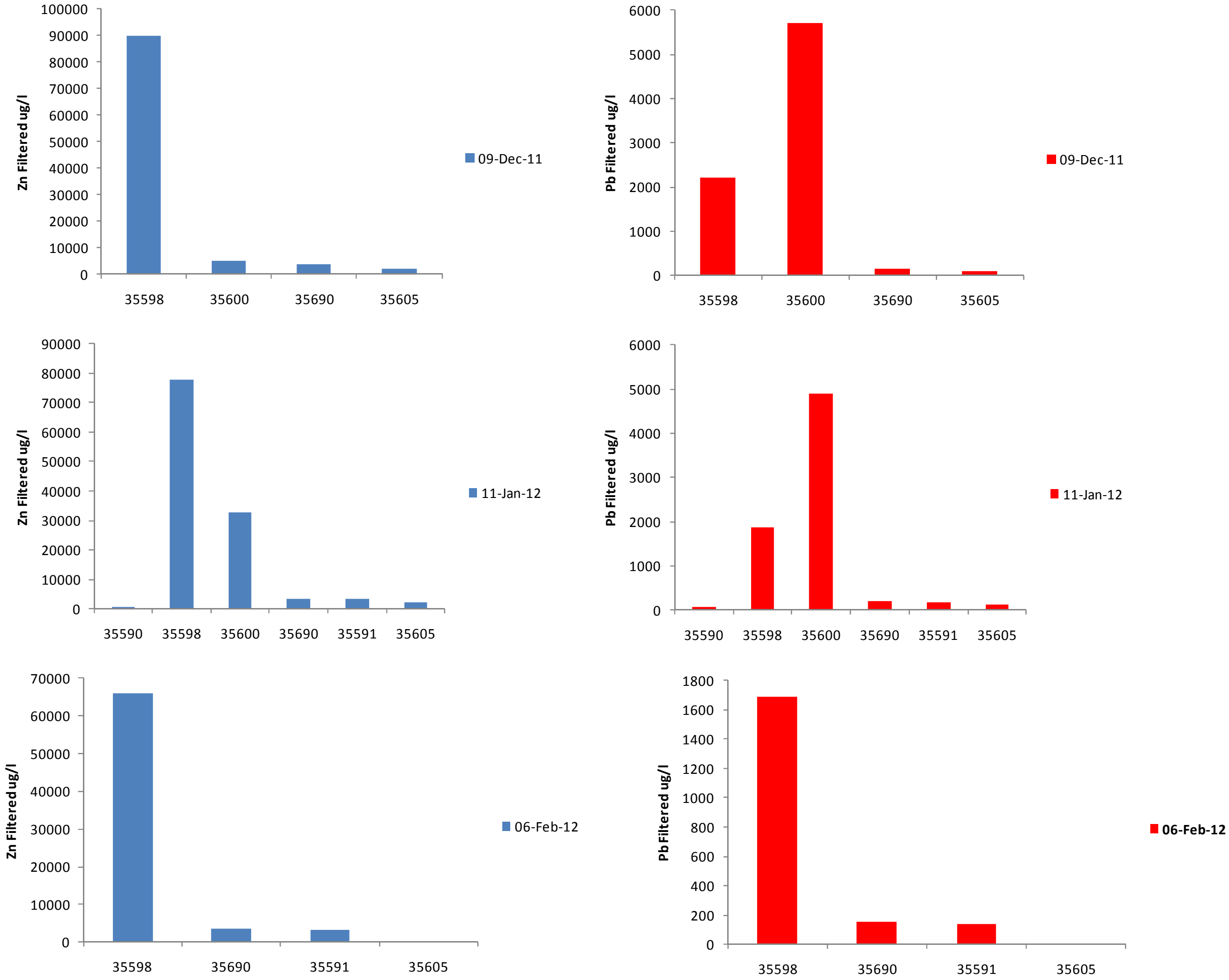


Figure 5.6 (continued)

Table 5.2 Estimated flows at Frongoch culvert

Date	Estimated Flow at the culvert (l/s)	
	Back-calculated based on Zn concentrations of Frongoch Stream and culvert	Back-calculated based on Pb concentrations of Frongoch Stream and culvert
15-Jul-2011	0.88	1.53
22-Aug-2011	0.34	0.46
22-Sep-11	6.44 *(measured= 5 l/s)*	9.84
03-Nov-2011	2.73	4.33
9-Dec-2011	3.67	6.32
11-Jan-2012	4.40	11.5
6-Feb-2012	2.81	5.05

The EA data are of limited use for a full mass balance, as they mostly do not include flow measurements except for the Frongoch Stream d/s the Frongoch mine tailings area (EAW point 35690).

A complete set of flow and chemical data for the 5 current EA monitoring points is available only for the 22/09/2011 as shown in Table 5.3. This sampling date followed a fortnight of intense rainfall. Based on the calculated loads (Table 5.4), the culvert with a flow of 5 l/s contributes 78% of the Zn fluxes in the Frongoch Stream, while the "surface water" contributes only 0.66%. Also, the culvert contributes 51% of the Pb fluxes in the Frongoch Stream, while the sampled surface water contributes 15 %.

Similar mass balance calculations have been undertaken for two further monitoring dates during summer, the 15th July and 22nd August 2011, when the flow at the culvert was very low (< 1 l/s), following relatively long (~ a week) dry weather spells. Assuming a flow at the culvert of 0.5 l/s, on 15th July the culvert contributes 57% of the Zn fluxes in the Frongoch Stream and 33% of the Pb fluxes in the Frongoch Stream, while the surface water contribution was nil. By increasing the estimated flow at the culvert to 0.8 l/s, the culvert contribution to the Zn fluxes is 90% and to the Pb fluxes 52%.

On the 22nd August 2011, assuming a flow of only 0.3 l/s the culvert contributes 89% of the Zn fluxes in the Frongoch Stream and 65% of the Pb fluxes.

Table 5.3 Zn and Pb concentrations at selected EA monitoring points on 22/09/2011

EAW points	Date	Time	Description	Pb-Filtered ug/L	Lead - as Pb ug/L	Zn-Filtered ug/L	Zinc - as Zn ug/L	Flow L/s
35598	22-Sep-11	1348	CULVERT ON FRONGOCH TAILINGS	2740	2700	101000	101000	5
35600	22-Sep-11	1335	SURFACE WATER FROM FRONGOCH TAILINGS	4580	14900	4770	5010	0.90
35690	22-Sep-11	1305	FRONGOCH STREAM D/S MINE	179	255	4320	4090	150.6
35605	22-Sep-11	1433	FRONGOCH STREAM ABOVE CONFLUENCE WITH NANT CELL	142		2820		286

Table 5.4 Zn and Pb loads at selected EA monitoring points on 22/09/2011

EAW points	Date	Time	Description	LOAD Pb Filtered kg/day	LOAD Lead kg/day	LOAD Zn Filtered kg/day	LOAD Zinc kg/day
35598	22-Sep-11	1348	CULVERT ON FRONGOCH TAILINGS	1.18	1.17	43.63	43.63
35600	22-Sep-11	1335	SURFACE WATER FROM FRONGOCH TAILINGS	0.36	1.16	0.37	0.39
35690	22-Sep-11	1305	FRONGOCH STREAM D/S MINE	2.33	3.32	56.21	53.22
35605	22-Sep-11	1433	FRONGOCH STREAM ABOVE CONFLUENCE WITH NANT CELL	3.51	0.00	69.68	0.00

Some further considerations can be made using the available chemical data relative to the culvert at the south east corner of the Frongoch tailings and the Frongoch Stream downstream of the mine tailings, plus the flow measurements of the latter. Back calculations, assuming that the culvert (EAW 35598) is the only point source of Zn and Pb to the Frongoch Stream at point 35690, estimate the flow at the culvert as shown in Table 5.2. There is a noticeable discrepancy between the flows back-calculated on the basis of Zn concentrations and those based on Pb concentrations. The flow estimates based on Pb were higher than those based on Zn concentrations and can be explained by either an unsampled input of Pb load in the mass balance or a non-conservative behaviour of Zn, which is attenuated downstream the culvert to the Frongoch Stream. Considering the much more soluble nature of Zn than Pb at the stream pH conditions, it is more likely that the difference in calculated flows is due to an unsampled diffuse input enriched in Pb to the stream. The chemical composition of surface water (EAW sample 35600), where available, supports this conclusion (Figure 5.6).

Considerable surface run-off during storm events has been observed in various occasions. However, the available dataset does not include monitoring data during storm events to allow quantification of the likely significant runoff component of metal loading to the Frongoch Stream.

6 Additional observations

6.1 CD/ZN AND PB/ZN WEIGHT RATIOS

The Cd/Zn and Pb/Zn weight ratios have been plotted against dissolved Zn concentrations (Figure 6.1).

The Cd/Zn weight ratio in the adit portal discharges remained fairly constant over the monitoring period 2004-2012. A constant ratio relative to increasing Zn concentrations indicates a constant mineral source input for these elements, which is likely to be sphalerite found in the ore deposit. A noticeably higher Cd/Zn weight ratio was determined in the mill pond water that entered the adit level before the stream diversion in March 2011. The contribution of freshwater to the adit, through rapid mixing and low residence time, may determine the spread of the Cd/Zn values in the adit discharge, observed before the diversion. Similarly, the Cd/Zn weight ratio in the Frongoch Stream remains fairly constant, while Zn concentrations become more diluted through mixing with fresh unpolluted water after the stream diversion.

The Pb/Zn weight ratios against dissolved Zn concentrations in the Frongoch Stream water is more variable indicating different potential sources for these elements or diverse mechanism of attenuation that differentiate them during down-gradient flow from the mine tailings.

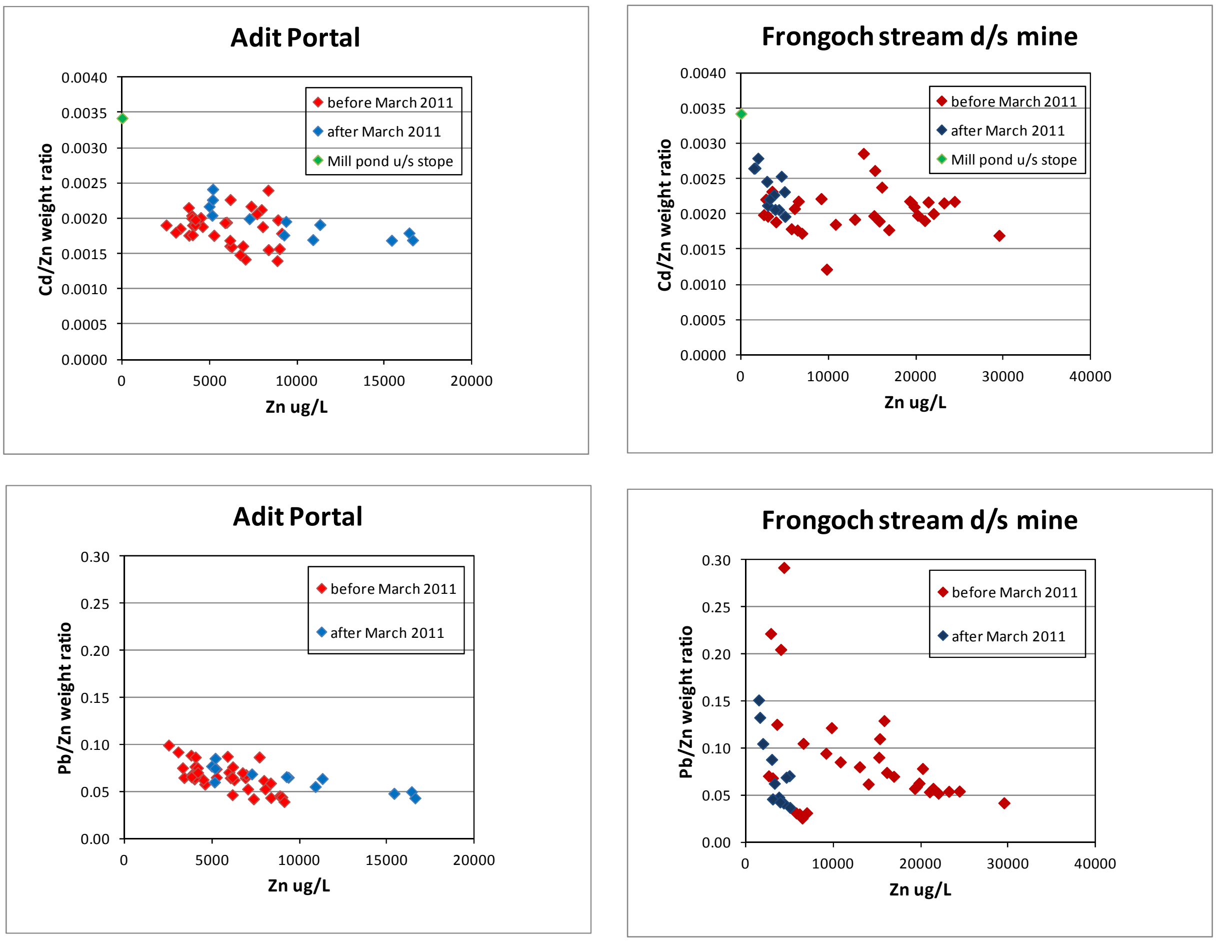


Figure 6.1 Plots of Cd/Zn and Pb/Zn weight ratios against Zn concentrations at the Frongoch Adit and Frongoch Stream d/s tailings area.

6.2 TEMPERATURE

Figure 6.2 shows the water temperature trends for the Frongoch Adit, the Frongoch Stream and the culvert seepage, with the culvert discharges showing less variable temperatures.

A marked difference in temperature among the groundwaters in the two boreholes and the surface water may be useful to trace the source of the water in the culvert. On the 7th February 2012 it was noticed that the culvert water had a temperature (8.9 °C) very similar to the groundwater from the deep borehole BH1 (8.8 °C) in the till and quite distinct from the Frongoch Stream upstream of the culvert (3 °C) or any ponded water on the tailings (3 to 4 °C) and also in borehole BH3 (4.9 °C). More data would be needed to confirm the temperatures that were observed on this occasion. On the same occasion, it was noted that the "surface water from Frongoch tailings", EA monitoring point ID 35600, had a temperature of 6.9°C, higher than any surface water on site. Previous temperature data from the EA database confirm that the samples have always higher temperatures than the Frongoch Stream and were closer to the culvert temperatures measured on the same monitoring occasions. It seems to suggest this monitoring point collects seepage water.

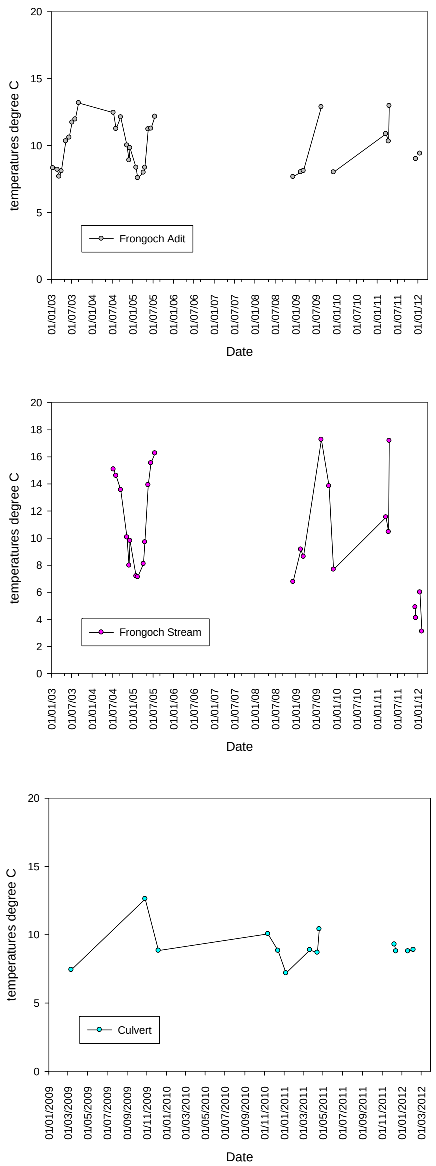


Figure 6.2 Temperature profiles for the Frongoch Adit, the Frongoch Stream and the culvert.

7 Conclusions

This report presents a review of the hydrogeochemistry of the Frongoch Mine, mid Wales, UK. Data available from the BGS and EA for use in this report included Pb and Zn concentrations of water samples, daily flow and spot flow measurements and daily rainfall measurements. These have been used as reported, and also been used to calculate loading and mass balance.

The objectives set out in the introduction of this report have been achieved as follows:

1) The EA and BGS water monitoring data are presented for Pb and Zn, the main elements of concern in the waters draining from the Frongoch site. These have been discussed in conjunction with rainfall and flow rates, and presented as loads and mass balances.

2) The effect of the stream diversion is discussed. As expected, the flow from the adit has decreased, while the flow in the Frongoch Stream has increased, but continues to be variable. This is because the Frongoch Stream receives water that overflows from the impounding mill pond, which is fed by the surface water discharge that formerly entered the mine workings via the Llwyn Shaft. The concentrations of Pb and Zn have responded to the changes in flow. In the adit the concentrations have increased, and in the Frongoch Stream the concentrations have decreased. This is a result of the effects of dilution. In contrast, the post-diversion loadings remain similar to previous loadings in both the adit and the Frongoch Stream.

3) Mass balance calculations using EA data have identified the culvert discharge as the major input source of Zn to the Frongoch Stream. Whilst the sampling frequency of the culvert is insufficient to draw definitive conclusions, the available data suggest that the contribution of the culvert discharge remains large at both high and low flows. A significant additional source of Pb loading to the Frongoch Stream, other than the culvert, is highlighted. The contribution of the surface runoff component of the metal load, which is recognised to be significant during storm events, cannot be calculated in absence of monitoring data related to those events.

   A mass balance for the Zn and Pb loadings in the Nant Cell was calculated using BGS unpublished data. A marsh area was identified as a contaminant store, but a more detailed study is needed to characterise this.

4) The discharge issuing from the Frongoch Adit is responsive to rainfall, peak flows rising sharply after high rainfall, and gradually declining afterwards. This reflects it being fed by groundwater from the mine workings and in part by infiltrating recharge at shaft locations. Further monitoring would aid in confirming this.

   The Frongoch Stream receives overland flow from the hillsides, and overflow from the pond, so the largest flow events may represent pond overflow, rather than direct response to recent rainfall.

   The data relative to the culvert are very infrequent and incomplete to allow confident interpretation of the results. It remains that discharge at the culvert can peak in response to rain events. Previous single borehole dilution tests indicated a low groundwater velocity of ~ 0.4 m/d in the tailings around borehole BH3. However, it is possible that a proportion of water in the tailings moves relatively quickly as preferential flow and could account for the relatively flashy hydrograph response to rainfall. Flow at the culvert, although very low (< 1 l/s), continued even during dry periods (e.g. April 2011) suggesting a matrix flow moving relatively slowly through the waste.

   Using the data available it is thought that the water draining from the culvert is derived from the perched water that borehole BH3 intercepts. This groundwater interacts directly with the reactive tailings and is thought to flow laterally to the culvert discharge.

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