TerraConsult

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HAFOD LANDFILL SITE

HYDROGEOLOGICAL RISK ASSESSMENT REVIEW

Prepared for

Cory Environmental (Central) Ltd

HAFOD LANDFILL SITE

HYDROGEOLOGICAL RISK ASSESSMENT REVIEW

December 2015

Carried Out For:

Cory Environmental (Central) Ltd

Prepared By:

TerraConsult Ltd
Bold Business Centre
Bold Lane
Sutton
St. Helens
WA9 4TX

Telephone: 01925 291111
Facsimile: 01925 291191
E-mail: mailbox@terraconsult.co.uk

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1. INTRODUCTION

1.1 Background

This document, prepared by TerraConsult (South) Ltd (TCL) was commissioned by Cory Environmental (Central) Ltd (CEL) to prepare a Hydrogeological Risk Assessment (HRA) Review for the Hafod Quarry Landfill Site in Wrexham, in line with the requirements to provide periodic hydrogeological risk assessment reviews during the operational life of the site.

As part of this HRA Review, the as-built engineering and groundwater quality has been reviewed to provide a basis for any recommendations regarding future management controls at the site.

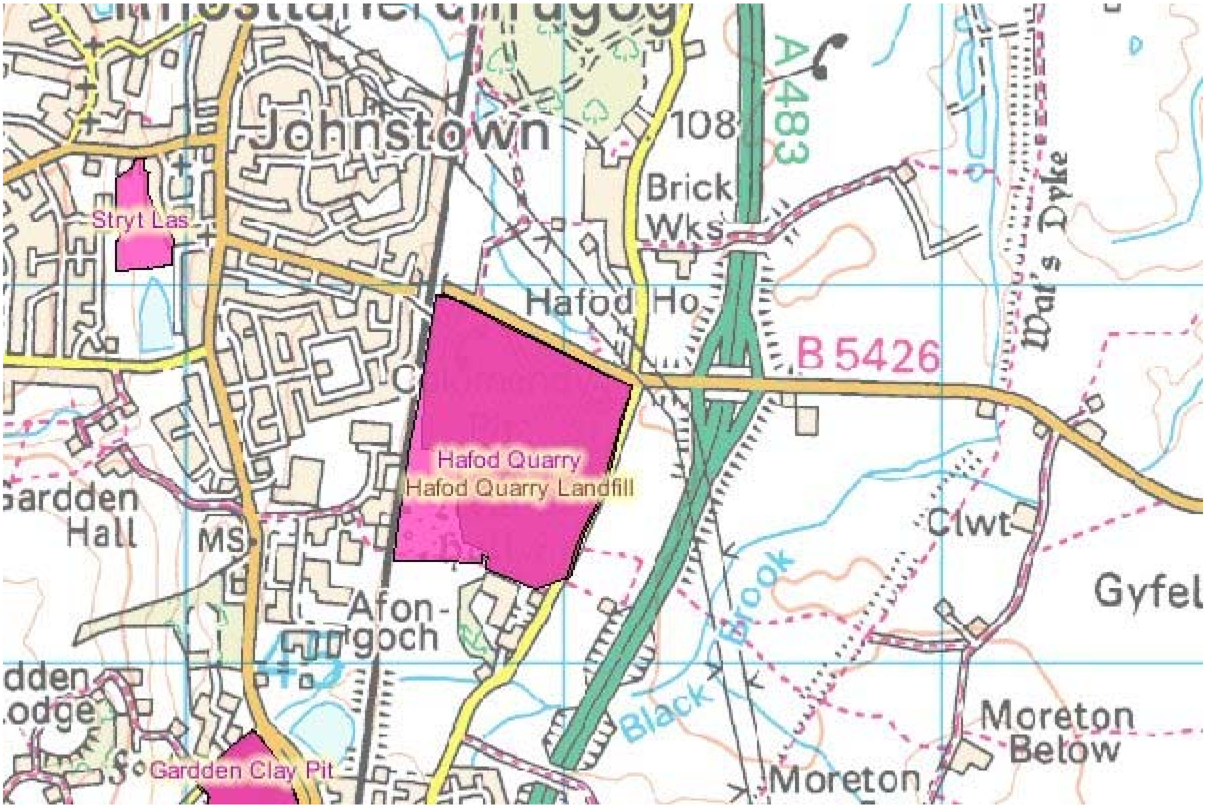
1.2 Site Location and History

Hafod Quarry Landfill Site, Bangor Road, Johnstown, Wrexham, LL14 6ET occupies an area of 28.6ha, located approximately 1km east of Johnstown and some 4km south west of Wrexham. The site is located at National Grid Reference (NGR) SJ3086 4554.

The site is bounded by the former Vauxhall Colliery to the south, an area which still contains abandoned spoil heaps. There is a railway and urban development of Johnstown to the west, the B5426 to the north, and New Hall Road before the A483 to the east of the site.

The local area was originally agricultural, and is still farmed to the east, north and south of the site. The landfill itself is located within a former quarry (exploiting the Etruria Marl (formerly Ruabon Marl mudstones) for brick clay, which overlies coal seams from the Carboniferous Middle Coal Measures. Quarrying and mining has occurred since the 1880's.

Figure 1 Site Location



The site was originally licensed for the permanent disposal of wastes in 1999 by Shropshire Waste Management Ltd. There has since been a succession of waste management licences which have now been fully superseded, namely:

Shropshire Waste Management Ltd	EAWML/3701 Issued 30/04/1999
Hafod Quarries Ltd	CG0323101, Issued 13/06/2000
SITA (Hafod Quarries Ltd)	CG0397901, Issued 25/05/2002
M W H Associates td	PPC Permit BS8621, Issued 08/10/2004

The site's PPC Permit was subsequently converted under the Environmental Permitting Regulations into an Environmental Permit and is currently operating to Environmental Permit EPR/PP3139GB for the disposal of inert and non-hazardous municipal, commercial and industrial wastes within engineering containment cells.

Landfilling commenced at the site in 2006.

1.3 Previous Risk Assessments

There have been three hydrogeological risk assessments undertaken for the site in addition to pre-operational site investigations.

- Encia Consulting Ltd (2003) Hafod Quarry Landfill Site, Hydrogeological Risk Assessment. Report 2425/2/RA
- Egniol Consulting Ltd (2009) Hafod Landfill Site, Hydrogeological Risk Assessment Review. Report B3112/HRA
- SLR Consulting Ltd (2010) Hafod Landfill, Hydrogeological Risk Assessment Review. Report 405-0281-00020

The 2003 HRA was prepared as part of the original PPC Permit application, whilst the 2009 HRA was produced in response for a 4-yearly review of the site's hydrogeological risk assessment. The 2010 HRA Review was produced to address outstanding queries raised by the Environment Agency. This review has been produced as the 2nd periodic review of the site's potential hydrogeological risk. However, since the issuing of the permit, the frequency has been reduced from 4-yearly to 6-yearly.

In addition to the previous HRA reviews, data and discussions provided within recent (2008 - 2014) annual monitoring reviews has also been considered within the preparation of this assessment.

2. SOURCE TERM

2.1 Site Engineering

To date, Cells 1 - 3 are operational. Cells 1 and 2 were operational prior to the production of the 2010 HRA review and disposal operations are currently being undertaken in Cell 3. A Construction Quality Assurance (CQA) Plan for Cell 4 was produced in July 2015 and construction works are in progress. It is expected that the Cell 4 CQA Validation report will be submitted to NRW before the end of 2015.

The site was originally (from March 2011) capped using 1m of site won clay, engineered to a hydraulic conductivity of <10^{-9}m/s as waste heights achieve their pre-settlement contours. Capping has progressed from the south of the site and placement of a permanent cap above Cell 2 is in progress during 2015. In addition a temporary LLDPE cap has been placed across the northern flank of Cell 3 to reduce rainwater ingress into recently operational areas and to assist with gas control.

Cell 3 construction was undertaken between August and October 2010[1] and operations commenced in February 2011.

Cell 3 has been constructed to the same design as Cells 1 and 2, and the design (as illustrated in Figure 2) comprises:

- Leachate abstraction riser;
- Herringbone patterned leachate drainage pipework within; a
- 300mm granular drainage layer;
- Geotextile protection layer;
- 1m thick engineered clay to a maximum hydraulic conductivity $1\text{x}10^{-9}$m/s; and
- Where the liner is not underlain by either Glacial Clay or Marl (*i.e.* the upper parts of the sidewall), an artificially established geological barrier has been constructed to the same engineering specification as the basal liner (*i.e.* to a combined thickness of a 2m mineral liner)
- Below sidewall liner drainage, provided by a geocomposite drainage layer with counterfort drains (to prevent pore pressure causing basal heave on the sides of the site)
- Below basal liner drainage provided by a geocomposite layer, with pipes to an abstraction sump.

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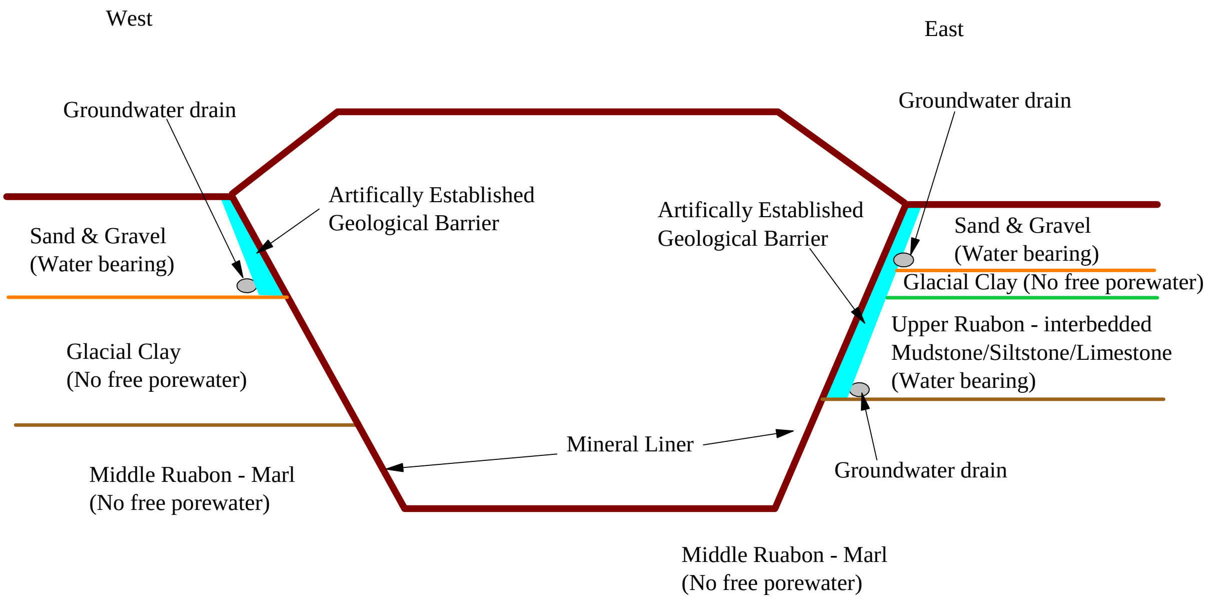
[1] Egniol (2010) Hafod Landfill Site. Cell 3 Phase 1 Construction Works - Construction Quality Assurance Report.

Figure 2 Schematic West - East Section through Cell 3



The base of the liner ranges from 70.24mAOD, increasing to 72.3mAOD on the west (CQA Drawing 5906a). The top of the liner was also sloped from a minimum of 71.8mAOD at the east of the cell, increasing to 73.4mAOD at the western edge of the cell base to enhance leachate collection (CQA Drawing 5906b).

The Cell 3 mineral liner was constructed to a standard in excess of the design criteria at a permeability of 6.3×10^{-11} to 9.1×10^{-10}m/s, with a most likely (median) hydraulic conductivity of 9.2×10^{-11}m/s.

The engineered thickness is also 10 - 20% greater than designed at 1.1 - 1.2m across the majority of the basal area, increasing to 1.5m on the east of the cell base (CQA Drawing 5906c).

This data is consistent with the previous model assumptions of a liner modelled based on cell construction data for Cells 1 and 2 and the permit requirements as

Minimum	6×10^{-11}m/s
Most Likely	1.2×10^{-10}m/s
Maximum	1×10^{-9}m/s (*i.e.* the permit requirements)
Thickness	1.0 - 1.15m

Landfill operations have progressed from the southern edge of the quarry in a northerly direction. Although primarily a below ground level landfill, the site can also be considered as a land raise scheme as the current topography has been raised from ~107mAOD adjacent to the site to 119mAOD in Cells 1 and 2. This height is however consistent with residual colliery spoil heap heights and hence the landfill will visually shield the colliery spoils from view towards the east. The site is permitted for a final landform of up to 133mAOD within the central area of the site, which will result in a waste thickness range of 15 - 61m, with an average thickness of 40m.

Surface water run-off from the majority of the landfilled area is shed by the cap away from the remaining quarry void, whilst each cell has been constructed with a surface water cut-off trench to divert surface run-off into the quarry void from entering the waste mass.

Water can enter the quarry void via two routes, the first is direct incidental rainfall and the second is from the superficial groundwater system. The site's geology comprises a sequence of:

- Glacial sand and gravels
- Boulder Clay
- Interbedded mudstone, siltstone and limestone
- Mudstone

Since the base of the site has been excavated into the lowest unit of this sequence, *i.e.* the mudstone (Figure 2), then groundwater from the more permeable strata discharges into the quarry void, unless diverted otherwise. CEL have therefore implemented a two-stage level of protection, namely by

1. Constructing a 1m @ 10^{-9}m/s artificially established geological barrier (AEGB) against any potential water bearing strata;
2. Constructing a groundwater drainage system behind the AEGB to relieve pore pressures and divert the intercepted groundwater from the sand and gravels or the limestone bands from acting on the sidewall.

The groundwater management system behind the sidewall AEGB comprises a geo-composite drainage layer with associated collection pipework in gravel filled trenches. Where possible, this drainage system has been designed to operate under gravity. Where gravity flow is not possible, sidewall risers are being installed to enable the groundwater to be diverted to a surface water lagoon and discharged under permit conditions to surface water.

Observations during cell construction have continued to demonstrate that there is no free porewater within either the Ruabon Marl or the Glacial Clay. Groundwater above the glacial clay is however recharged from the west with an easterly gradient. Consequently there is a greater potential pressure acting on the western perimeter (the upgradient side) than the eastern perimeter, which is considered to be on the downgradient edge.

2.2 Leachate Volume

The volume of leachate within the site has been difficult to establish due to silting of monitoring points as well as failure of some wells.

Leachate is currently tankered off-site for treatment and disposal.

A leachate management plan for the site was developed in April 2015 which explains that CEL's preferred regulatory option[2] for the disposal of landfill leachate is on-site treatment and then disposal to sewer. However, this potential is limited and not economically possible as although the leachate could be treated to an acceptable standard, Welsh Water are reluctant to grant a Trade Effluent Discharge Consent (TEDC) due to the site's location

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[2] Environment Agency Guidance Water Discharge and Groundwater (from point source) Activity Permits (EPR 7.01)

within the Upper Dee catchment, upstream of a major drinking water abstraction at Chester. This reluctance is not associated with any toxicity or harmful chemical issues, but is due to the potential for ‘tainting of the taste’ of the water from the salt content and residual stable (recalcitrant) organic constituents within the leachate after treatment both on-site and at a receiving sewage treatment works.

Leachate management has to date been restricted by the practicalities of transferring leachate to Flintshire County Council’s Brookhill Leachate Treatment Plant (LTP). After preliminary trials to demonstrate efficacy, the limitations on leachate removal are due to capacity issues at the receiving works. Consequently CEL have obtained planning permission to install additional leachate holding capacity at the site to enable the constant draw down of leachate within the site, whilst maximising the potential for utilising spare capacity at the Brookhill LTP. A long-term commercial arrangement is being negotiated with Flintshire County Council for the receipt of this leachate. However, during 2014 and 2015 site records also demonstrate that leachate was also tankered to treatment plants at Davyhulme, Ellesmere Port and Monkmoor, although this practice is not sustainable due to the distances involved.

Given the limitations on the ability of the site to remove leachate (as discussed above) and the foaming within monitoring wells, it is difficult to fully understand the extent of leachate within the site. Foaming is a natural occurrence from the agitation of dissolved natural organic matter, such as fulvates and other molecules, which will be contained within the leachate and comprise a significant proportion of the COD. Agitation can occur from abstraction and perched leachate decanting into wells above the standing water level, as well as any disturbance from abstraction.

Notwithstanding the above, the height of foam within wells would appear to indicate a high leachate level, in the order of 15 - 20m. However, where foaming effects can be excluded from the data set, leachate heights are negligible at the abstraction points, and at the Cell 3 abstraction point in particular (Figure 3). A more representative leachate height acting on the base of the site was derived from transducer measurements and data from re-drilled monitoring points. These investigations identified that the leachate height is between 2m and 3m above the base of Cells 1 and 2 as explained within the April 2015 leachate management plan[3].

Installation logs for the most recent installation in November 2015 confirms the minimal leachate volume within the waste as dry waste was recorded for the first 30m of the waste column with saturated waste only present within the basal <4m of the installation. Therefore, if there is free leachate at a higher elevation, this free leachate must be perched.

The relatively low standing leachate head acting on the base of the site can also be inferred in part derived from conclusions drawn from leachate removal rates from the site, which demonstrated that after the initial trial period average daily removal rates were within the 80 - 100m^3/day range, which have latterly stabilised at 55 - 65m^3/day (Figure 3). The fact that a sustainable leachate volume in the order of 60m^3/day can be obtained from Cells 1 - 3 is demonstrative of an effective basal collection infrastructure, that can transmit a large volume of leachate in excess of expected leachate generation rates, which would limit the potential for a leachate head to act on the base of the site.

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[3] Cory Environmental (Central) Ltd (April 2015) Hafod Quarry Landfill Site. Leachate Management Plan V2.1

Notwithstanding the issue of an actual relatively low leachate head, which equates to 73 - 75mAOD, it is considered appropriate to consider the height of the leachate 'foam' and perched water levels to provide commentary on the risk to the hydrogeological system. Significantly, as discussed within later sections of this review, even if the leachate perched water and / or foam height is considered as representative of leachate heights, the leachate remains hydraulically contained and hence of negligible pollution potential (Figure 4)

Figure 3 Leachate Height Vs Volume, 2008 - November 2015

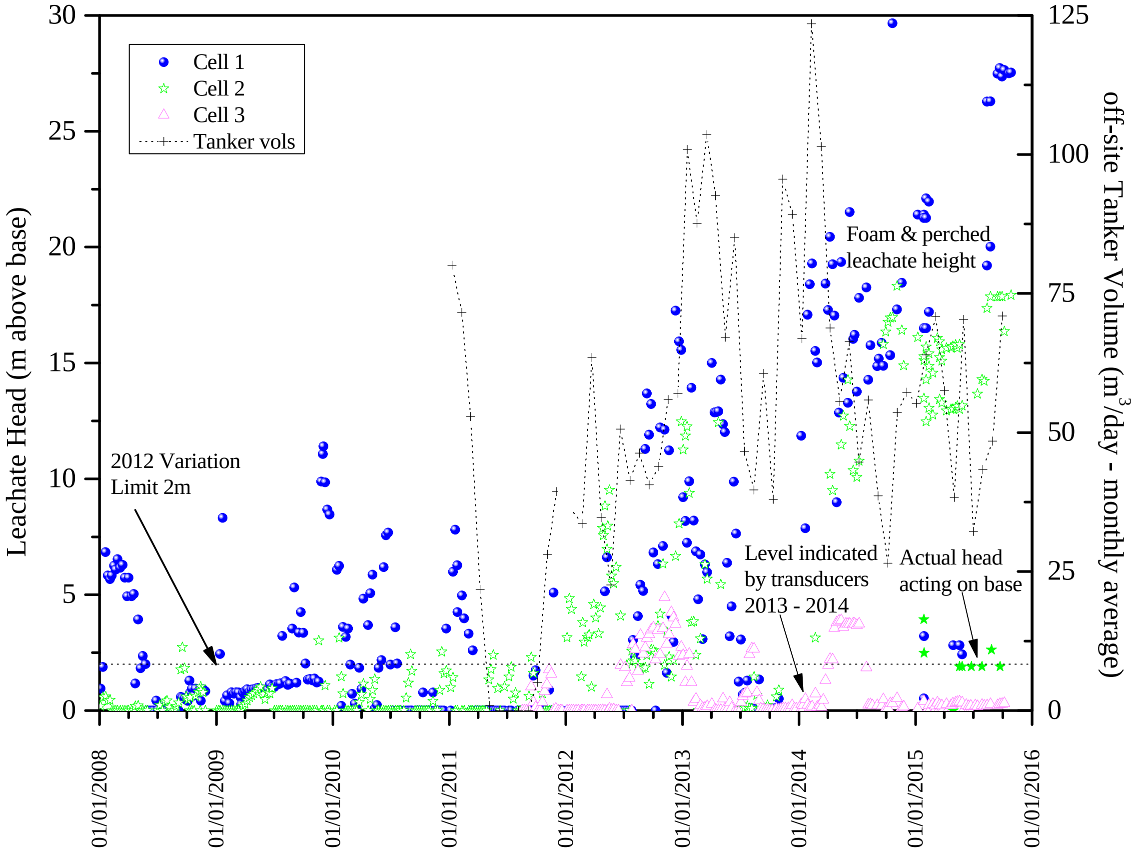
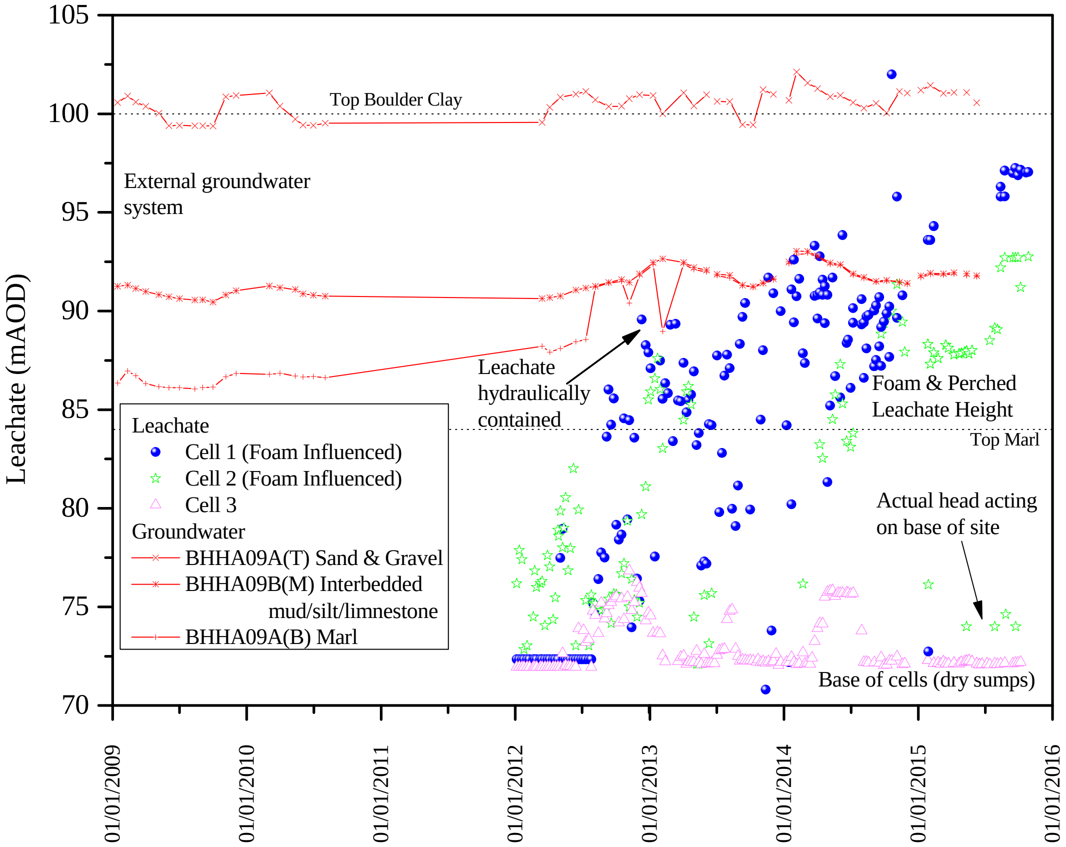


Figure 4 Leachate Level Compared to the Adjacent Groundwater System



2.3 Leachate Quality

Matrix Chemistry

The leachate chemistry appears to be stabilising at a composition consistent with that expected from a non-hazardous landfill, namely a sodium-bicarbonate-chloride solution, with significant ammoniacal-N, potassium and recalcitrant dissolved organic matter (Table 1, Figure 5 - Figure 7). The recent BOD is a consequence of relatively young wastes and is expected to reduce as each cell matures and the degradable component of the dissolved organic matter is biologically transformed into the methane and carbon dioxide component of the landfill gas.

Table 1 Leachate Chemistry Summary (Annual Average Concentrations, 2012 - 2014 and Maximum 2015)

Location	Year	NH_4-N	COD	BOD	Chloride	Alkalinity	Sulphate	Potassium	EC
		mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	µS/cm
Cell 1	2012	2,350	9,500	435	2,700	5,200	338	430	24,550
	2013	2,075	6,875	1,662	2,400	11,750	292	828	18,653
	2014	2,450	8,850	4,980	2,350	13,000	93	680	28,100
	2015 Max	3,000	13,000	3,100	5,700	13,000	580	1,300	33,400
Cell 2	2012	2,233	12,000	1,967	2,567	9,633	273	697	22,080
	2013	1,536	9,975	1,618	2,626	11,825	103	654	15,832
	2014	1,180	16,150	3,300	2,450	12,900	31	620	24,200
	2015	3,000	3,300	220	2,000	5,700	3	560	19,000
Cell 3	2012	1,640	22,000	4,700	3,000	6,900	122	935	21,050
	2013	1,257	4,800	573	2,633	8,467	270	837	19,600
	2014	1,700	4,400	130	2,600	8,600	70	880	24,500
	2015 Max	2,000	13,000	6,200	4,300	7,200	460	960	27,300

Figure 5 Cell 1 Leachate Matrix Chemistry

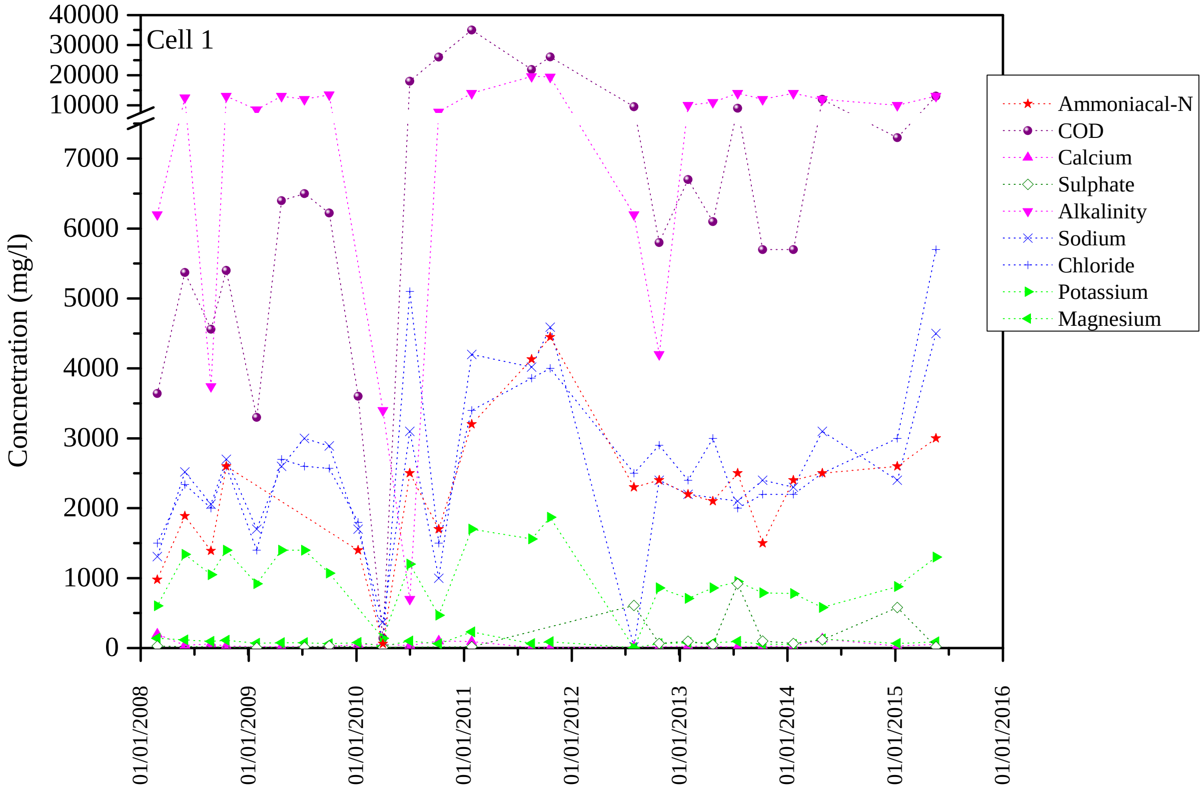


Figure 6 Cell 2 Leachate Matrix Chemistry

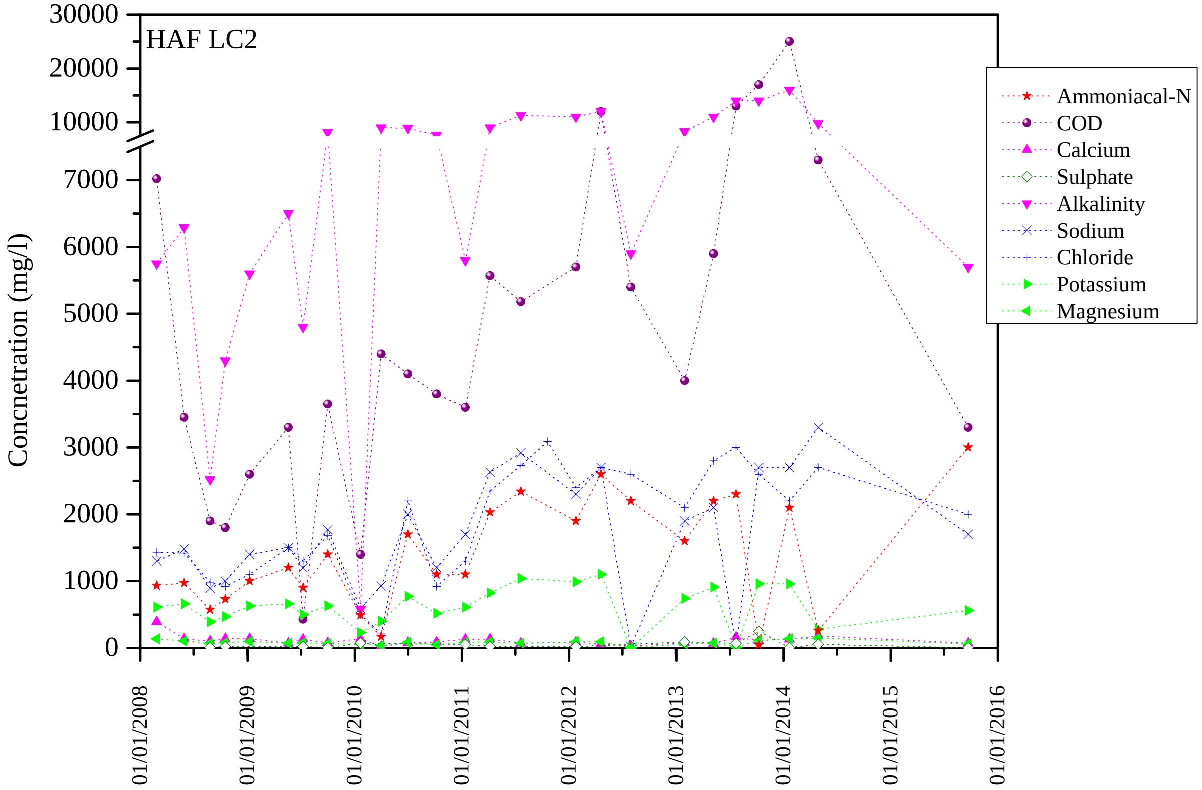
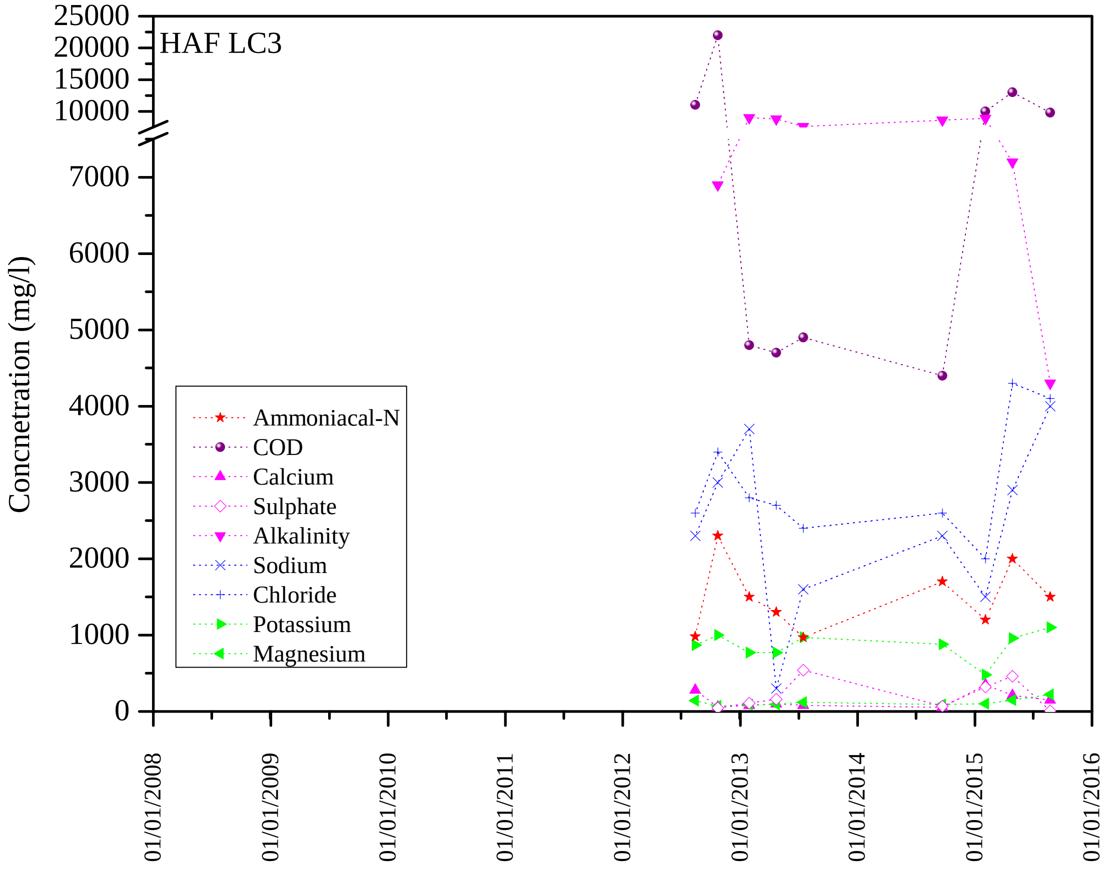


Figure 7 Cell 3 Leachate Matrix Chemistry



Non-hazardous Substances

There is a consistency in the non-hazardous metal composition within the leachate across the cells (Figure 8) which can be summarised as:

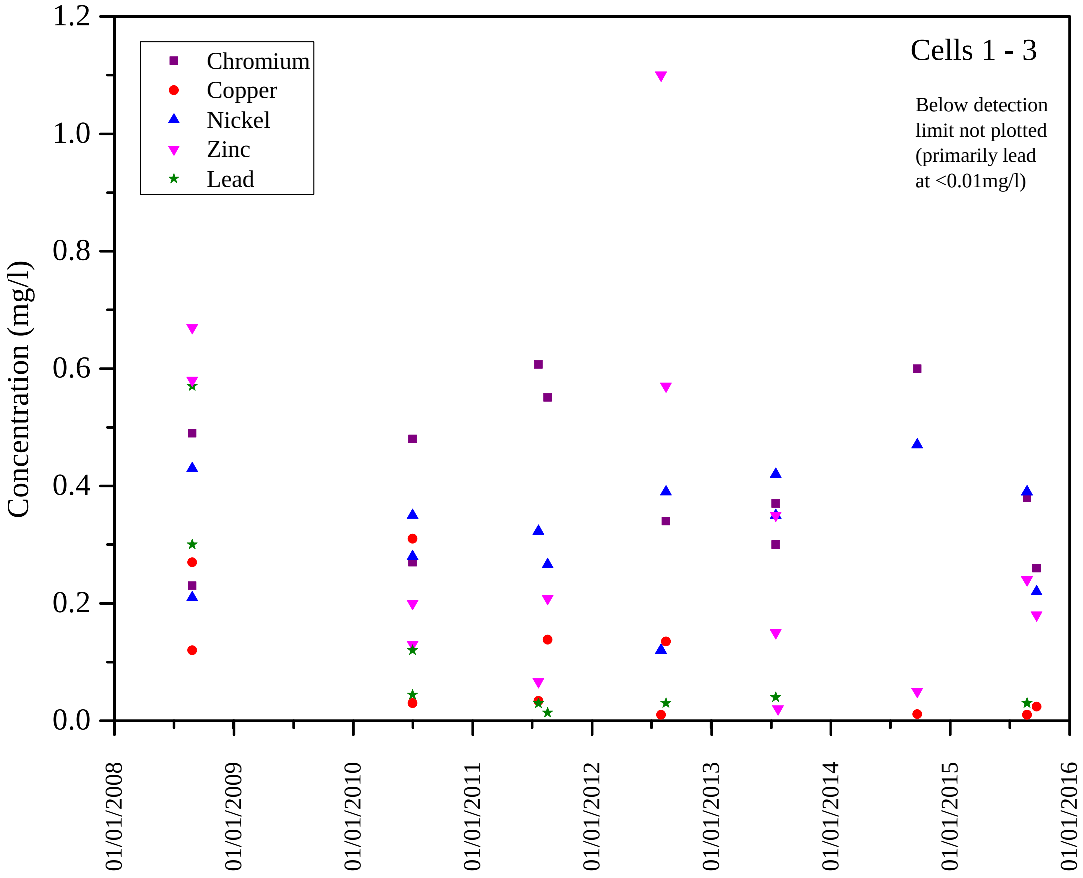
Chromium at	0.23 - 0.6mg/l
Nickel at	0.21 - 0.47mg/l
Copper at	<0.01 - 0.31mg/l
Lead at	<0.01 - 0.04mg/l

Zinc shows a greater variability at 0.02 - 0.67mg/l than those detailed above, with a single outlier at 1.1mg/l. However, although zinc concentrations can be apparently high, the highest concentrations are inconsistent with a soluble form, and are representative of either a particulate or a colloidal form. Significantly, both of these forms would be physically filtered by the clay liners and are of no relevance to seepage, particularly as the leachate source concentrations are below the zinc Drinking Water Standard of 5mg/l.

Of the remaining non-hazardous metals, both lead and copper are typically below the 10µg/l detection limit and hence either approximate to or are below their respective DWS of 0.01mg/l and 2mg/l respectively.

Chromium and nickel are the most significant non-hazardous constituents within the leachate as they are the only metals consistently in excess of their 0.05mg/l and 0.02mg/l DWS. However, it should be noted that chromium cannot persist as the Cr(VI) form under the methanogenic conditions within the site. It is highly likely that given the low solubility of all Cr(III) forms under the leachate pH, then the chromium is associated with the suspended solid component, whilst nickel is the most likely non-hazardous metal to be present within a mobile form, namely as an organic colloid.

Figure 8 Leachate Non-hazardous Metals



Hazardous Substances

Mercury has not been reported within the leachate, whilst cadmium is below both the 5µg/l DWS and the 1µg/l leachate screening level identified within Annex J3 of the H1 Environmental Risk Assessment Guidance.

The organic components present within the leachate (Table 2) are a function of the maturity of the leachate, *i.e.* the methanogenic conditions have not developed completely and a proportion of the short-lived hydrolysis products (namely the organic acids and phenols) which make up the BOD and are causing the leachate foaming are not being completely degraded at source. Consequently there are still discernible substituted phenols within the leachate, of which 4-methylphenol is the primary constituent. These phenols have an extremely short half-life under both anaerobic and aerobic conditions when solubilised in the order of hours to days and hence are not classified as hazardous, are not persistent or have any environmental significance at their leachate concentrations.

The primary leachate constituents are the BTEX compounds and similar substituted aromatics, which are present at <1 - 30µg/l. The BTEX substances are, like the phenols, a primary breakdown product of natural organic matter and are primarily removed as part of the landfill gas. Polycyclic aromatic hydrocarbons are also at low concentrations and cumulatively are below the 10µg/l leachate screening level[4].

Chlorinated solvents, pesticides and herbicides (*e.g.* mecoprop is reported as <0.02µg/l) do not appear to be present within the leachate.

Table 2 Leachate Dissolved Hazardous Substances and Organic Screen (Substances Present above Detection Limits)

Substance	Unit	Cell 1	Cell 1	Cell 2	Cell 2	Cell 3	Cell 3	Cell 3
		Jul-13	Oct-15	Jul-13	Sep-15	Jul-13	Sep-14	Aug-15
Cadmium	µg/l	<0.03	1	0.4	<0.1	0.6	0.2	0.2
Phenols	µg/l	<0.1	3500	4200	6	3800	<0.3	490
2-methylphenol	µg/l	56	63	<50	<1	<50	10	<1
4-methylphenol (p-cresol)	µg/l	2700	24,000	3100	16	1600	<0.3	510
3&4-Methylphenol	µg/l	2500	4600	3700	<1	620	39	<1
2,6-Dimethylphenol	µg/l	<0.25	<0.1	28	<1	<0.25	<0.3	<0.1
2,4-Dimethylphenol	µg/l	37	<0.1	<1	<1	11	<0.3	<0.1
Aniline	µg/l	120		<50	<1	<50	43	2
Benzene	µg/l	<1	12	<1	6	<1	4	<1
Toluene	µg/l	3	25	<1	28	<10	13	10
Ethyl benzene	µg/l	1	17	<1	13	<10	10	4
m,p-xylene	µg/l	<1	18	<1	18	<10	29	6
o-xylene	µg/l	1	12	<1	11	<10	17	3
Styrene	µg/l	<1	1	<1	1	<1	2	1
1,3,5-Trimetylbenzene	µg/l	<1	4	<1	2	<1	3	<1
1,2,4 trimethylbenzene	µg/l	1	12	<1	6	<10	8	2
p-Isopropyltoluene	µg/l	2	21	<1	8	<10	2	<1
PAH (Sum of EPA 16)	µg/l	<0.2	2	5	0.6	1	3	<7
Chlortoluron	µg/l	5.8	<1	3	<0.5	4	<1	<0.5
Diuron	µg/l	5.6	<1	<5	<0.5	20	<1	<0.5
Linuron	µg/l	<0.5	<1	5	<0.5	5	<1	<0.5
Monuron	µg/l	13.4	<1	1.1	<1	<0.05	<1	<0.5
2,2-dichlororopane+1,2-dichloroethylene	µg/l	<1	<1	<1	<1	20	<1	<1
1,1-dichloroethylene	µg/l	2	<1	<1	<1	<10	<1	<1
Methylene chloride	µg/l	31	<27	<27	<27	<27	<27	<27

Note methylene chloride is laboratory solvent used for SVOC separation prior to analysis. Phenols is not a specific test for phenol (*i.e.* C_6H_5OH) and applies to all phenolic substances including fulvates & humates, as well as the mono-substituted phenols.

Previously commentary has been made as to the reported EPH content of the leachate, which has been reported in the 10 - 25mg/l range in previous years. However, this analysis is not specific to extractable petroleum hydrocarbons (EPH) and is only applicable for determining refined petroleum products where there is no other dissolved organic matter. It is a completely unsuitable and erroneous analysis with respect to landfill leachates as the bulk organic constituents including all of the fulvates and humate components which make up the chemical oxygen demand and the total organic carbon content of the leachate are co-eluted within the EPH extraction process and therefore any results reported are

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[4] Environment Agency (Dec 2011) Horizontal Guidance Note H1 - Annex J3. Additional guidance for the hydrogeological risk assessments for landfills and the derivation of groundwater control levels and compliance limits. Appendix 6 - Analytical framework for screening landfill leachates. Tables A6.1 - A6.3

representative of this fraction. Given that the hydrocarbons in question (*i.e.* the C10 - C40 fractions) are expected to be rapidly degraded within an active moisture rich biological system, the likelihood of these hydrocarbons being present within the reported range, or even at an environmentally significant concentration is considered negligible.

It is therefore recommended that the EPH test is discontinued for landfill leachates, or if undertaken, all reported data is treated with caution.

2.4 Leachate Summary

The leachate is a relatively low risk solution with respect to persistent contaminants. Hazardous substances are either at low concentrations within the leachate; whilst the specific organic substances that can be identified have short degradation half-life's and will not persist within the environment.

Nickel and chromium are the only persistent contaminants of potential concern with concentrations in the 0.2 - 0.6mg/l range; both metals have a high attenuation capacity and are not expected to migrate at an environmentally significant rate through a landfill liner.

There is potentially a short term effect from elevated BOD which will not persist after methanogenesis becomes fully established. In the longer term, leachate salinity, and ammoniacal-N are the most environmentally significant constituents. Of these, ammoniacal-N is the most significant leachate constituent, as leachate concentrations of 970 - 3,200mg/l range (Figure 9) are significantly in excess of the 0.39mg/l DWS, whilst chloride at 2,000mg/l - 4,300mg/l is only 10 - 15 times the 250mg/l DWS (Figure 10).

Figure 9 Leachate Ammoniacal-N

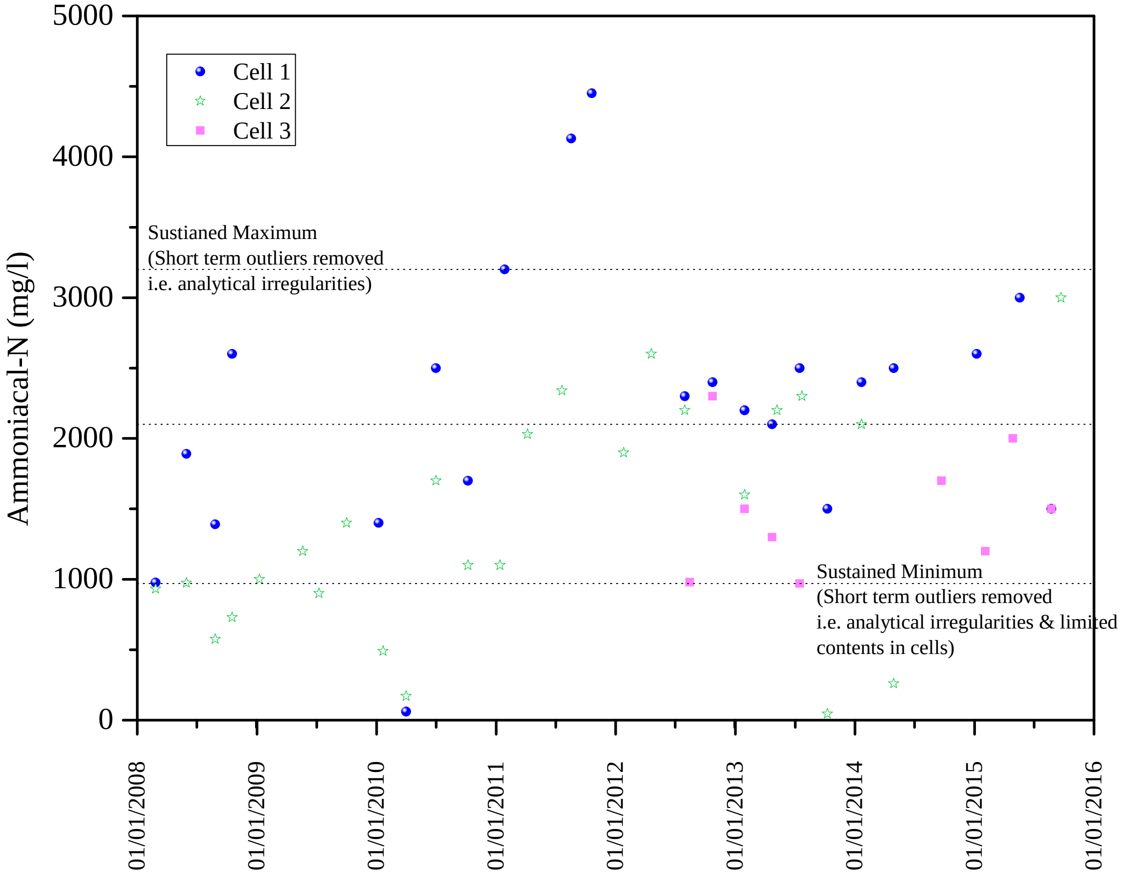
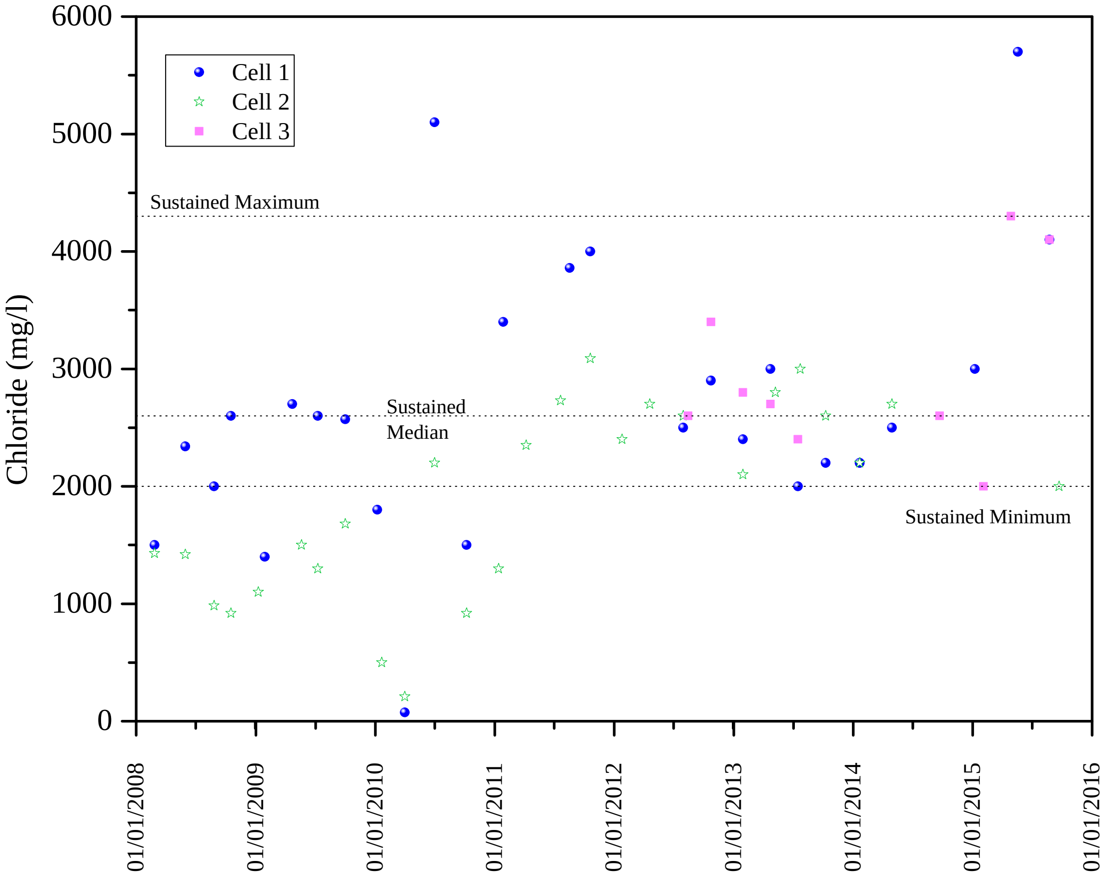


Figure 10 Leachate Chloride



2.5 Previously Modelled Leachate Inventory

The previous hydrogeological assessments and reviews considered a wide number of substances as illustrated in Table 3. The data demonstrates that the leachate had only begun to stabilise when the 2010 HRA review was undertaken.

Three conclusions can be drawn by the direct comparison, namely that:

1. The primary leachate constituents chloride and ammoniacal-N are elevated compared to the previous assessments;
2. Nickel and chromium are generally consistent, although slightly elevated than that previously considered; and
3. All other persistent and non-persistent contaminants of concern are at a significantly lower risk potential than previously assumed.

The key conclusion to draw is that any risk profile previously considered for hazardous substances is an over-estimation of the actual risk presented by Hafod landfill site. For example cadmium and mercury are below drinking water standards and there is a limited presence of specific organic components, and those that are consistently present are the expected products of biodegradation.

The potential impact from nickel and chromium will however remain consistent with previous expectations, whilst, that for ammoniacal-N and chloride should be reconsidered, although any risk cannot be realised at the leachate heights indicated by previous transducer investigations. The potential risk remains low even if leachate heights are assumed at the leachate foaming heights as even under this scenario the leachate is hydraulically contained and hence there is not the potential for migration under a driving hydraulic gradient.

Table 3 Leachate Source Term Comparison

Determinand	2003 HRA (Inferred Source)	2010 HRA Review (2008- 2009)	Recent Data
	mg/l	mg/l	mg/l
Ammoniacal-N	1,010 - 1,674 - 2,100	575 - 1,592 - 2,650	970 - 2,100 - 3,200
Chloride	300 - 909 - 1,720	920 - 1,884 - 7,760	2,000 - 2,600 - 4,280
Arsenic	0.005 - 0.219 - 0.59	Not in permit	Not analysed
Chromium	0.159 - 0.438 - 0.702	0.005 - 0.49	<0.01 - 0.355 - 0.607
Copper	0.005 - 0.044 - 0.059-	0.005 - 0.27	<0.005 - <0.010 - 0.31
Nickel	0.025 - 0.139 - 0.249	0.005 - 0.43	0.01 - 0.337 - 0.47
Cadmium	0.0025 - 0.0101 - 0.105	0.0005 - 0.0029	<0.0001 - <0.0005 - <0.001
Mercury	0.00004 - 0.00009 - 0.00195	<0.0001 - 0.0009	<0.0001 - <0.0003 - <0.0005
Mecoprop	0.00005 - 0.04 - 0.1	No data	$<2x10^{-5}$ - $<2x10^{-5}$ - 0.121
Phenol	0.00005 - 0.01 - 0.1	No data	$<5x10^{-4}$
PCE	0.00005 - 0.01 - 0.1	No data	<0.001
Naphthalene	0.00005 - 0.01 - 0.1	0.00507 - 0.0132	<0.001
Aliphatic C_5-C_{16}	0.00005 - 0.01 - 0.1	>C_6 - C_{40} 0.00005 - 0.000872	Not analysed
Aliphatic C_{17}-C_{35}	0.00005 - 0.01 - 0.1		Not analysed
Aromatic C_5-C_{16}	0.00005 - 0.01 - 0.1		Toluene <0.001 - 0.028 Xylene <0.001 - 0.029
Aromatic C_{17}-C_{35}	0.00005 - 0.01 - 0.1		<0.007

Specific petroleum hydrocarbons analysis has not been performed, to enable full separation of non-refined petroleum hydrocarbons (*i.e.* fulvates, humates etc.) from the mixture.

3. PATHWAYS

3.1 Geology and Hydrogeology

The underlying geological sequence at the site was originally described as glacial sediments overlying the Ruabon Marl as per the following sequence:

Western Perimeter	Eastern Perimeter	
Glacial outwash Sand and Gravel		Water bearing
Glacial Clay	Glacial Clay	Aquiclude
	Interbedded Upper Ruabon limestone / siltstone / mudstone	Water bearing in limestone bands
Middle Ruabon Marl (Mudstone)		Aquiclude

Since the preparation of the 2003 and 2010 HRA's the background geological nomenclature has been revised, and the Ruabon Marl has been re-classified as the Etruria Marl within the vicinity of the site. For consistency with the previous reports, the Ruabon nomenclature has been retained for this assessment.

A conceptualisation of the geological sequences is presented in Figure 2 and detailed cross-sections were presented within the 2010 HRA review, as SLR Drawing HRAR1.

The key features of the hydrogeological setting is that the site is located within a former sand and gravel quarry, which was then exploited for brick clay. The base of the site has therefore been constructed within a geological barrier, provided by the Lower and Middle Ruabon Marl. No useable water resources have been identified beneath the Lower Ruabon Marl, although the site is underlain by Coal Measures which were the subject of active mining.

The Upper Ruabon Marl comprises a 10m approximately 50% mudstone, which has been interbedded with limestone and siltstone bands. The limestone bands are water bearing and classified as a Secondary Aquifer and are capped by upwards of 1.5m of Glacial Clay.

The Upper Ruabon interbedded sequence is absent to the west of the site, where the *in-situ* geological barrier provided by the Middle Ruabon mudstone is continued vertically by an additional thickness of Glacial Clay, which has been attributed[5] to a paleo valley feature centred to the northwest of the site in which the Upper Ruabon unit appears to have been eroded and was subsequently infilled by up to 26m of Glacial Clay.

The Glacial Clay is overlain by glacial outwash Sand and Gravel. These, in common with the Upper Ruabon Marl are classified as a Secondary Aquifer.

It is noted that water ingress is not observable through the clay sidewalls of the quarry or into the groundwater drainage layer. However, water ingress into the quarry void is observable primarily from within the sand and gravel horizons on the west of the quarry, with a secondary component from the east. This ingress water is intercepted to prevent it from entering the waste mass and discharged to surface water via settlement ponds.

These observations are consistent with the hydrogeological properties of each section of the sequence

- Glacial Sand and Gravel 0.0003m/s
- Glacial Clay - negligible permeability (unproductive strata)
- Upper Ruabon Marl (10m Interbedded mudstones, siltstones & limestone)
  - 50% mudstone (negligible permeability); interbedded with
  - siltstone and fine-grained limestone at hydraulic conductivity of 10^{-5}m/s
- Middle and Lower Ruabon Marl, *in-situ* hydraulic conductivity of 10^{-10}m/s

The Sand and Gravel as well as the limestone bands are classified as secondary aquifers.

3.2 Groundwater Level

Clarification of the groundwater levels and the response zones monitored was requested by the Environment Agency within the 2010 HRA Review. The same nomenclature has been used within the preparation of this HRA Review, as summarised in Table 4 and Figure 11 - Figure 13.

The data demonstrates that groundwater within the immediate vicinity of the site is stratified to

- A superficial system at 96 - 106mAOD at the site;
- An Upper Ruabon limestone system at 91 - 95mAOD; and
- An inconsistent Middle Ruabon Marl system from 65 - 87mAOD

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[5] MJCA (1999) A Geological Summary of the Hafod Quarry Ground Investigation

There is a northwest to southeast hydraulic gradient, with a southerly component to the superficial groundwater flow, which is consistent with a fall in topography from 106mAOD on the west of the site to 96mAOD 300m to the east of the site at the A483. However, interpretation of the data appears to be complicated by leakage between the response zones and it is apparent that the superficial system is influencing the lower groundwater systems.

Water levels within the superficial and the Upper Ruabon system are consistent with a limited consistent seasonal trend, whilst the response zone within the mudstone is more variable, which is consistent with strata with a negligible groundwater flux potential.

Of these groundwater monitoring points, the key location is BHHA09B(M), as this monitoring point, located at the southeast corner of the site, contains the lowest groundwater elevation (at 92.1 - 93.0mAOD) which can be attributed to the interbedded Upper Ruabon Limestone, Siltstone and Mudstone units, and hence the key reference point for measuring the potential for hydraulic containment.

Previously a SE to NW hydraulic gradient was postulated for the Upper Ruabon Formation, however, there is insufficient clarity in the dataset to confirm such a definitive gradient from the current monitoring schedule.

However, it is noted that the ground elevation at the A483 at 96mAOD is consistent with a direct recharge to the Upper Ruabon Limestone and Siltstones, whilst the quarry void and the active dewatering necessary to reduce the pressure acting on the sidewall engineering (against the water bearing strata) would provide a localised influence on the adjacent groundwater levels. However, these are expected to return to the pre-operational levels once landfilling has advanced.

Table 4 Groundwater Summary (Jan 2013 - Jun 2015)

Sand & Gravel			**Limestone/Siltstone**			**Ruabon Marl**		
BH	**Min**	**Max**	**BH**	**Min**	**Max**	**BH**	**Min**	**Max**
	mAOD	**mAOD**		**mAOD**	**mAOD**		**mAOD**	**mAOD**
HA1A(T)	98.4	99.6	HA1B(M)	92.1	93.7	HA1B(B)	92.1	93.7
HA2A(T)	105.8	106.9				HA2B(B)	71.2	86.8
HA2A(M)	105.9	106.6						
						HA4(B)	105.4	106.8
HA5(T)	102.4	102.9				HA5(B)	107.7	108.9
HA6A(T)			HA6A(M)	99.5	102.0	HA6A(B)	84.9	86.8
HA6B(T)	101.3	105.1						
HA9A(T)	99.4	102.1	HA9B(M)	91.2	93.0	HA9A(B)	89.0	92.9
HA10(T)	91.3	93.0	HA10(M)			HA10(B)	91.2	92.3
HA11B(T)	101.4	102.5	HA11B(M)	91.4	93.2	HA11A(B)	91.2	95.6
HA12A(T)	*93.8	*94.9				HA12B(B)	93.2	94.3
HA12A(M)	93.1	94.6						

*Insufficient volume to sample

Figure 11 Groundwater Elevation (All Locations)

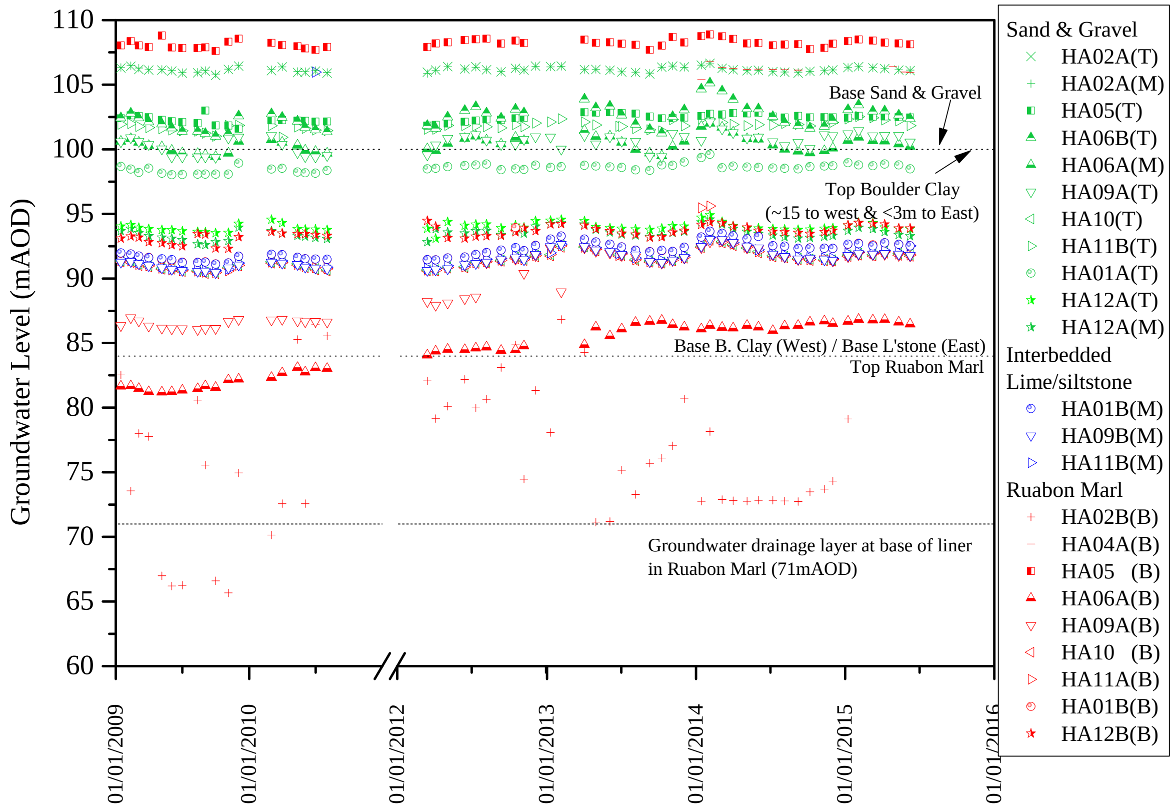


Figure 12 Sand & Gravel (Superficial) Groundwater Level

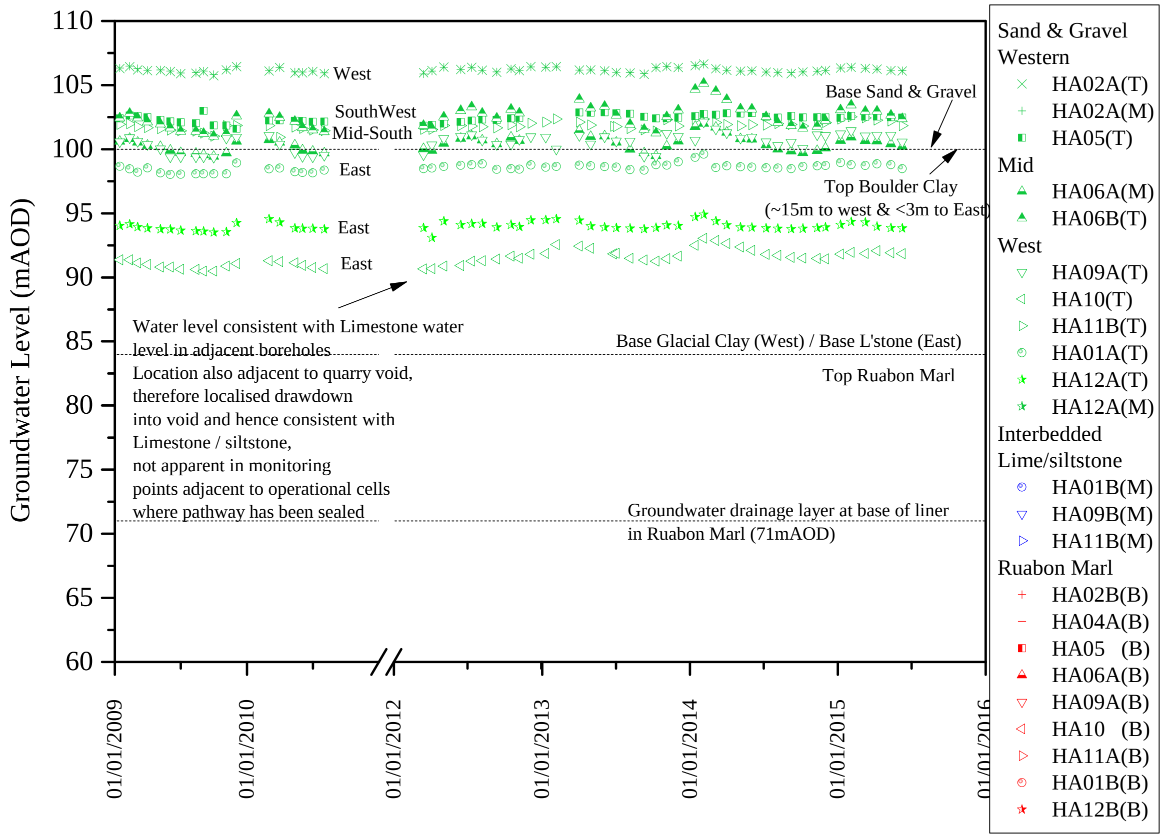
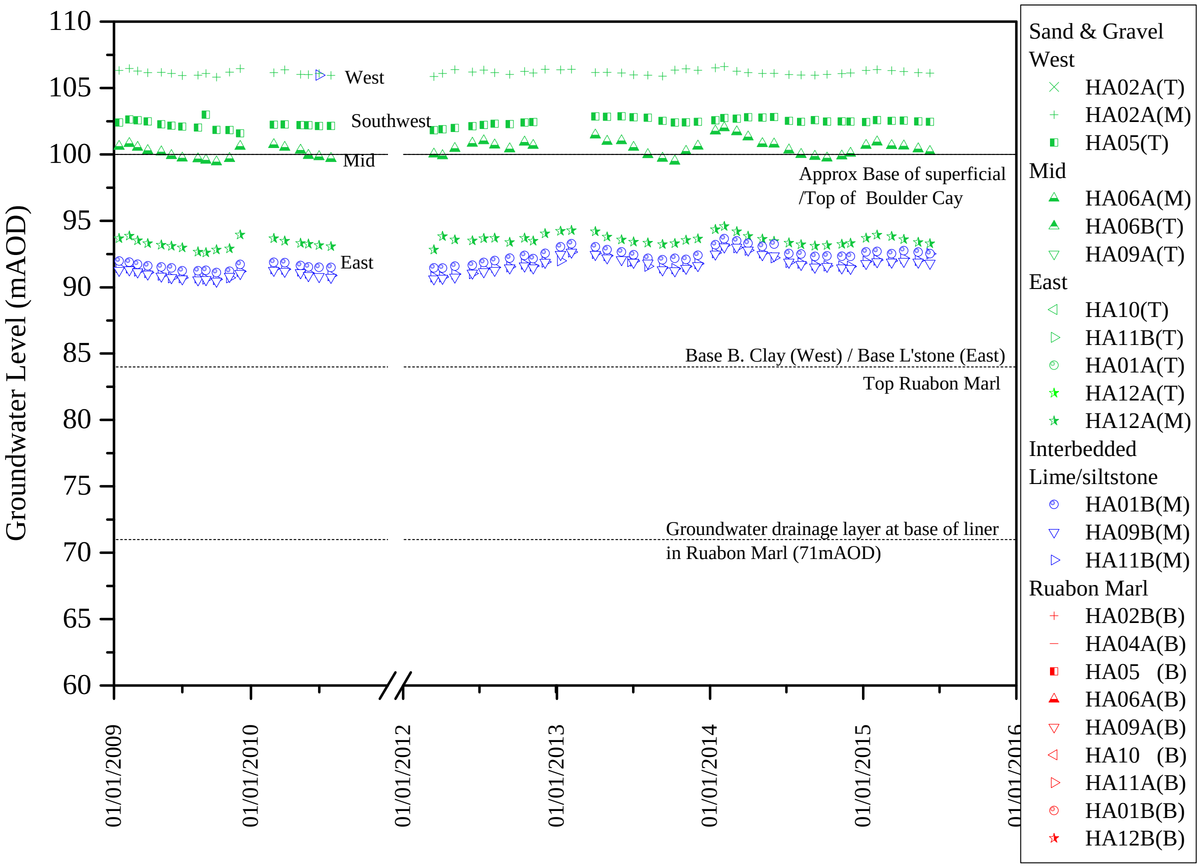


Figure 13 Upper Ruabon Limestone & Siltstone Groundwater Level



3.3 Hydrology

The site is bounded to the north by Aberderfyn, a surface water course which flows from the north, easterly along the northern perimeter of the site until New Hall Road, before flowing around the northeast corner of the site, then towards the east and under the A483.

The site's surface water is discharged, into the Aberderfyn from lagoons at the northwest and northeast corners of the site.

The elevation of the Aberderfyn at ~100mAOD at the edge of the site indicates that it is topographically above the leachate level within the site and hydrogeologically separate from the groundwater in the limestone, with the Glacial Clay providing a physical separation of water bodies within the immediate vicinity of the site.

4. RECEPTORS

4.1 Groundwater

The Hafod landfill site is not located within a groundwater source protection zone.

The glacial clay and the mudstone units of the Etruria Marl (Ruabon Marl) are classified as unproductive strata. This is confirmed from observations of the quarry sidewalls and during the construction of new cells, where seepages cannot be observed, indicating that the mudstones do not contain a free pore solution.

The sand and gravel and the non-mudstone strata within the Etruria Marl (*i.e.* the limestone bands), where present, are classified as secondary aquifers.

The site is therefore constructed within a geological barrier, with near surface water bearing strata.

4.2 Groundwater Quality

Matrix Chemistry

Groundwater chemistry (Table 5) has been reviewed regularly as part of annual monitoring reviews. These reviews have concluded that the groundwater is primarily a calcium carbonate based solution with a secondary calcium sulphate component (Figure 14), consistent with other confined limestone and Marl groundwaters in the UK, whilst the principal leachate constituents chloride (at <20 - 125mg/l, Figure 15) and ammoniacal-N (Figure 16) are negligible in comparison and environmentally insignificant. Time series plots for each location are appended.

Table 5 Groundwater Summary (Jan - Jul 2015)

BH HA	NH_4-N		COD		Ca		Mg		Na		K		Cl		SO_4		Alkalinity	
	Ave	Max	Ave	Max	Ave	Max	Ave	Max	Ave	Max	Ave	Max	Ave	Max	Ave	Max	Ave	Max
	mg/l																	
Western Locations																		
2A(T)	1.15	7.60	<20	<20	130	130	18	19	21	22	4	5	46	50	98	100	353	360
2A(M)	0.57	1.80	<20	<20	90	93	21	21	66	70	3	3	32	36	123	130	373	390
2B(B)	1.90	4.60	<20	23	27	37	7	7	200	230	7	7	54	60	4	5	553	580
4(B)	1.41	4.90	27	44	58	82	6	8	147	190	7	8	11	14	74	90	490	560
5(B)	0.17	0.23	<20	<20	130	140	24	24	23	24	10	10	77	83	98	100	335	350
Southwest Cell 1																		
6B(T)	0.04	0.05	<20	<20	330	370	46	47	28	29	15	15	34	37	745	770	405	410
6A(M)	0.22	0.25	<20	<20	120	120	24	24	38	38	4	4	33	35	195	200	330	340
6A(B)	0.38	0.57	<20	<20	14	14	3	3	215	230	6	6	35	36	130	130	405	410
Northeast Active Cells																		
1B(M)	0.36	0.96	<20	<20	217	240	46	47	51	53	6	7	77	84	407	430	427	440
1B(B)	0.47	0.68	<20	24	136	160	35	38	128	170	8	9	77	84	310	390	410	460
East of Active Cells																		
11B(M)	0.70	2.90	<20	<20	99	100	50	52	10	11	9	10	24	32	105	110	390	390
11A(B)	0.30	0.74	<20	<20	125	140	44	47	17	29	11	13	75	83	145	150	355	360
10(B)	0.58	1.10	<20	<20	77	95	25	32	171	330	8	9	76	83	230	380	423	530
10(T)	0.49	2.10	<20	<20	113	130	38	42	41	57	11	14	78	89	98	100	343	350
9B(M)	0.20	0.37	<20	<20	110	110	23	25	36	39	6	7	108	120	69	69	320	330
9A(B)	0.14	0.19	<20	<20	99	100	26	27	44	48	7	7	43	46	140	140	330	360
300m East of Site (on A483 Slip Road)																		
12A(M)	0.08	0.23	<20	<20	150	160	23	26	108	120	3	3	230	300	133	140	327	330
12B(B)	0.20	0.44	<20	<20	56	67	10	12	807	980	8	9	1,229	1,500	447	480	317	330

shaded cells indicate non-landfill sodium chloride influence

Figure 14 Hafod Geochemical Regimes

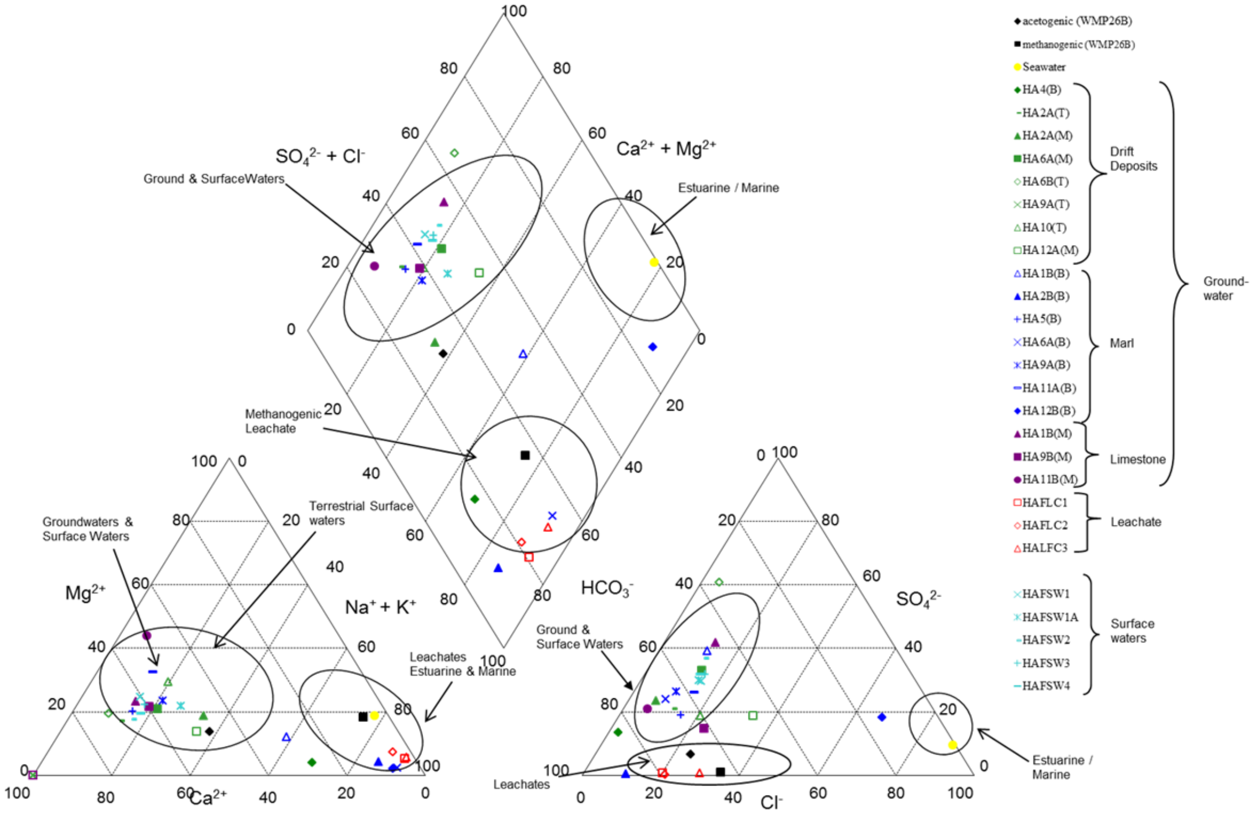


Figure 15 Groundwater Chloride

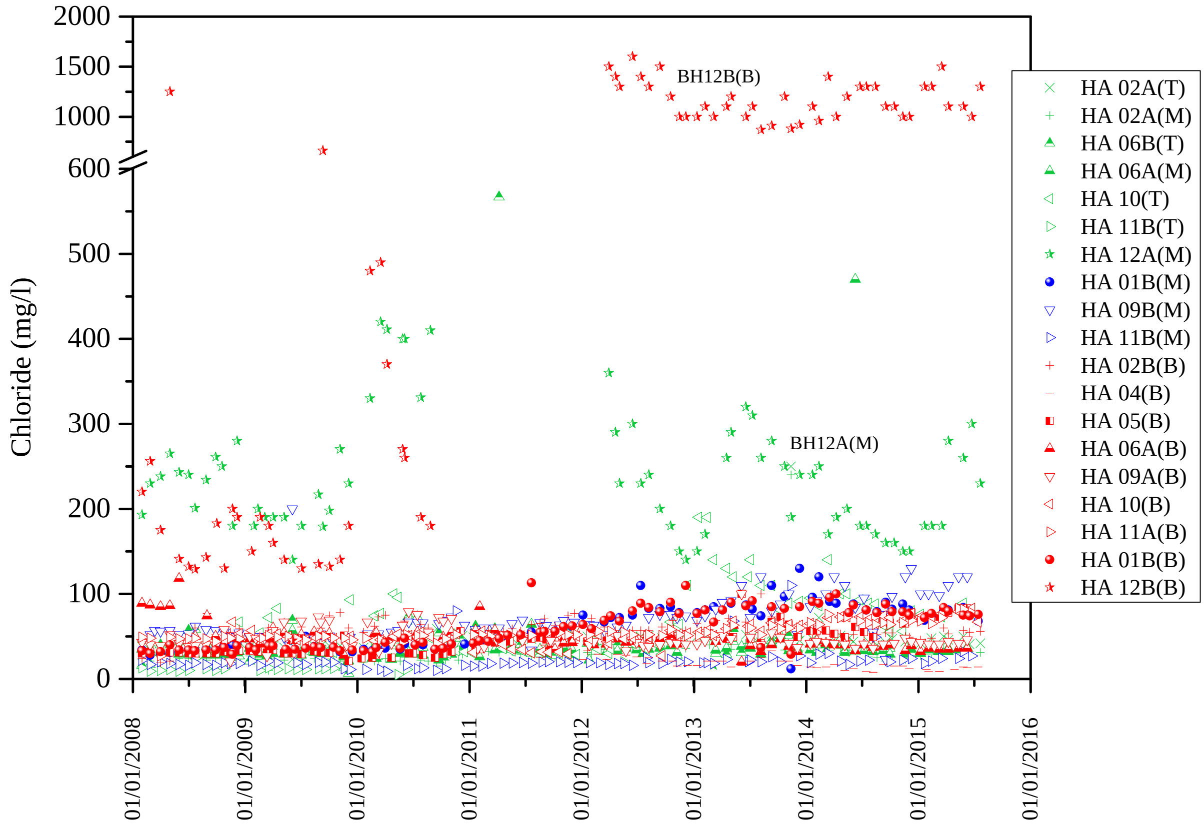
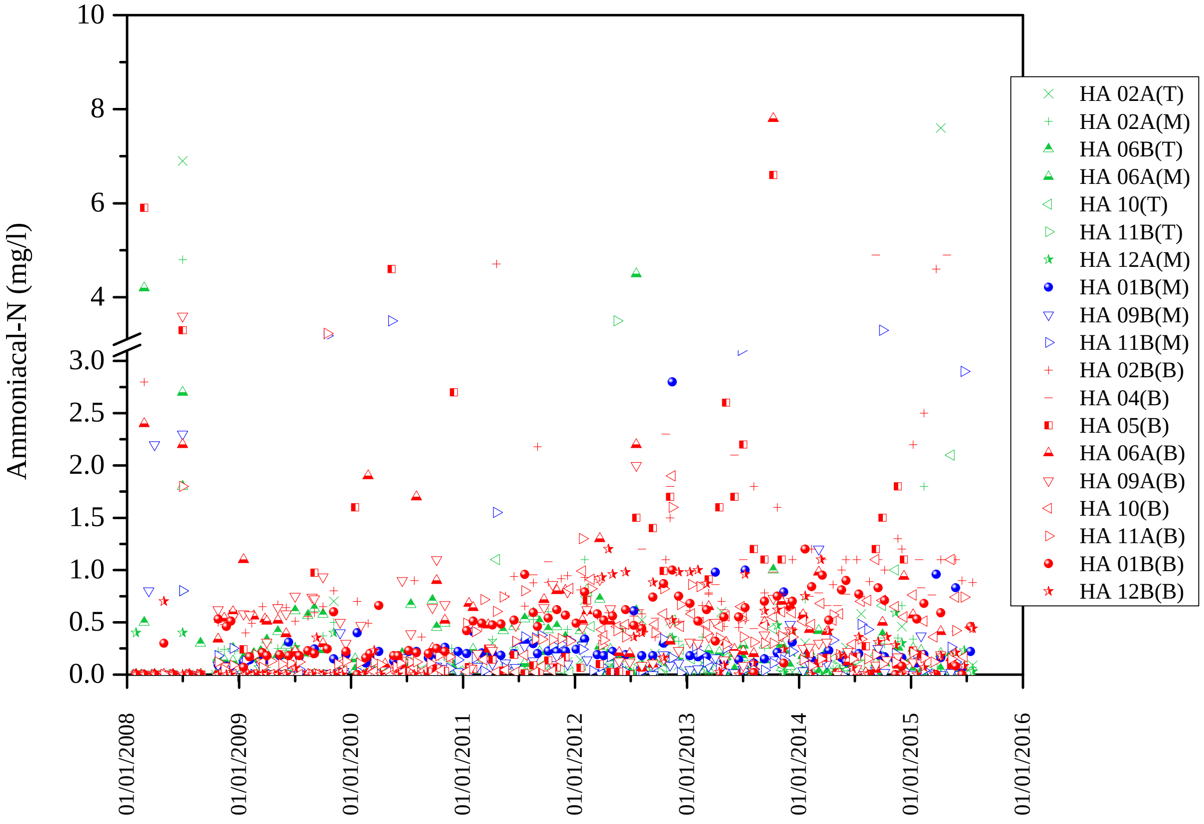


Figure 16 Groundwater Ammoniacal-N



The only distinguishing factors in groundwater quality are associated with the western locations, where the limestone units are not present. It is therefore unsurprising that HA06A (Marl), HA02B (Marl) and HA04(B) have consistently been identified as being depleted in calcium although enriched in sodium bicarbonate, compared with other locations. It is significant that chloride, the most mobile leachate constituent, is relatively depleted at these locations, hence the cause cannot be due to landfill leachate migration. This relative decrease in chloride is also associated with the most elevated ammoniacal-N (at HA02) the location in the northwest of the site with the highest groundwater levels and the greatest physical separation from the active cells.

The other anomaly is associated with monitoring locations with prefix HA12 are located adjacent to a major road and physically separated from the site, where sodium chloride is highly enriched to >1,000mg/l chloride. A similar enrichment is not observed at the BH11 series of monitoring points located adjacent to Cell 2, in which chloride is over an order of magnitude lower at <50mg/l in the limestone. Since BH11 would be preferentially impacted before the BH12 series of monitoring points, an alternative off-site source is suspected, which could include either road salt, or a natural evaporite horizon within the response zone.

It is noted that HA12A(M), the response zone in the limestone units does show a strong seasonal trend from 100 - 400mg/l. The concentration range is significantly higher at HAB(B), in the 1,000 - 1,500mg/l range. However, as groundwater levels between these monitoring points cannot be readily distinguished (Figure 11), it cannot be established if HA12B(B) is forming a conduit to groundwater for road-salt contaminated run-off water, or it is due to a response zone located near an evaporite horizon within the marl. It is also significant that the observed sodium chloride anomaly is also associated with an increase in sulphate and a slight depletion in potassium. There is negligible dissolved organic carbon (as represented by a COD <20mg/l) and ammoniacal-N is typically <0.02mg/l, with only the occasional spikes to <0.5mg/l in the current year. Such a relationship is inconsistent with leachate migration.

A non-landfill source is also suspected for the increase in chloride observed at both HA01 and HA09. The increase in chloride is consistent for both locations (Figure 17), with as near an identical increasing trend as is likely to occur. However, although HA09 is located adjacent to Cell 1 at the southeast corner of the site, there is a physical separation between the operational cells and HA01 at the northeast corner of the site. Therefore any change could not be due to leachate seepage from the engineered cells.

Further confirmation of a non-leachate source is that ammoniacal-N at HA09 has remained at negligible concentrations (*i.e.* <0.02mg/l), whilst potassium, which is significantly enriched in landfill leachates including those at Hafod is following a static, if not slightly depleting trend (Figure 18).

In contrast to HA09, HA11B(M) shows an apparent cyclic trend in ammoniacal-N from <0.02mg/l to ~0.5mg/l, with the occasional unsustained peak at up to 3.3mg/l. However, potassium appears to also follow a reducing trend, whilst chloride has remained static over time, with no apparent increasing trend and therefore the ammoniacal-N cannot be associated with leachate seepage from the landfill, but is consistent with seasonal off-site influences, such as manure spreading in adjacent fields (Figure 19).

Figure 17 Ammoniacal-N and Chloride at Eastern Locations

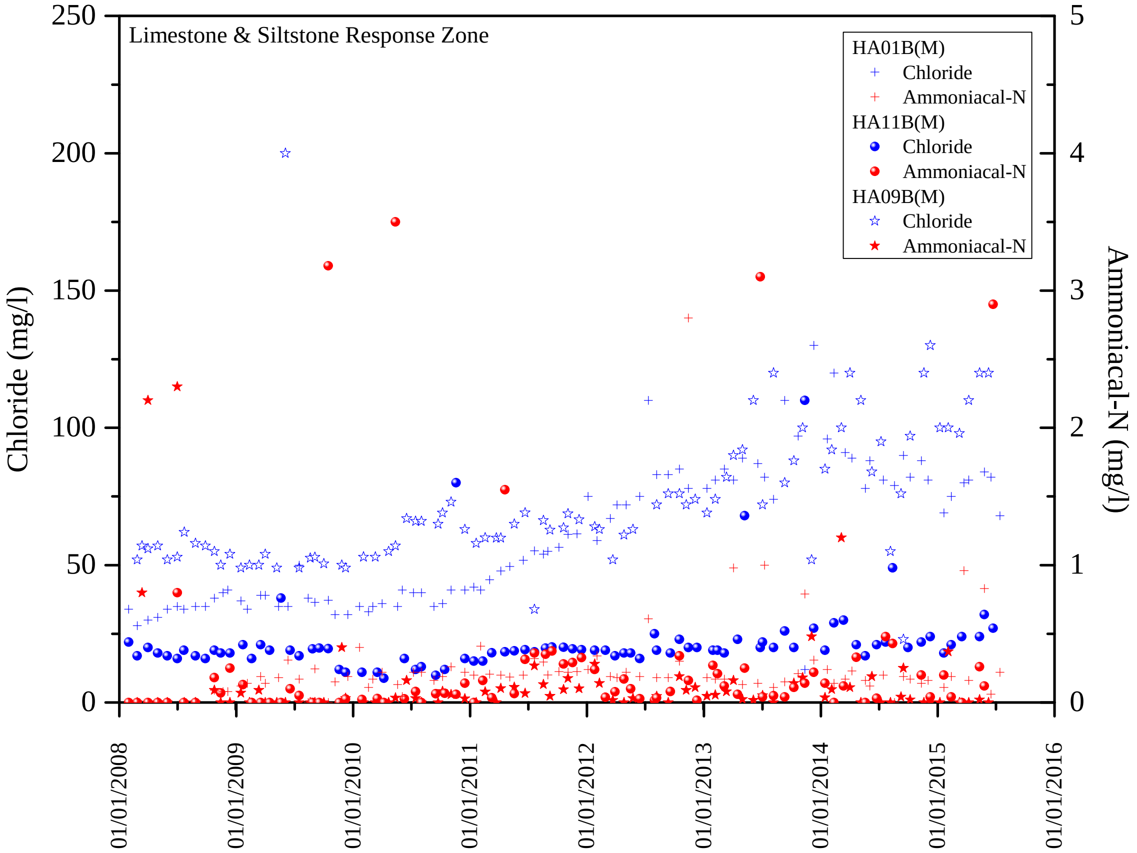


Figure 18 Primary Leachate Indicators at BH09B(M) East of Cell 1

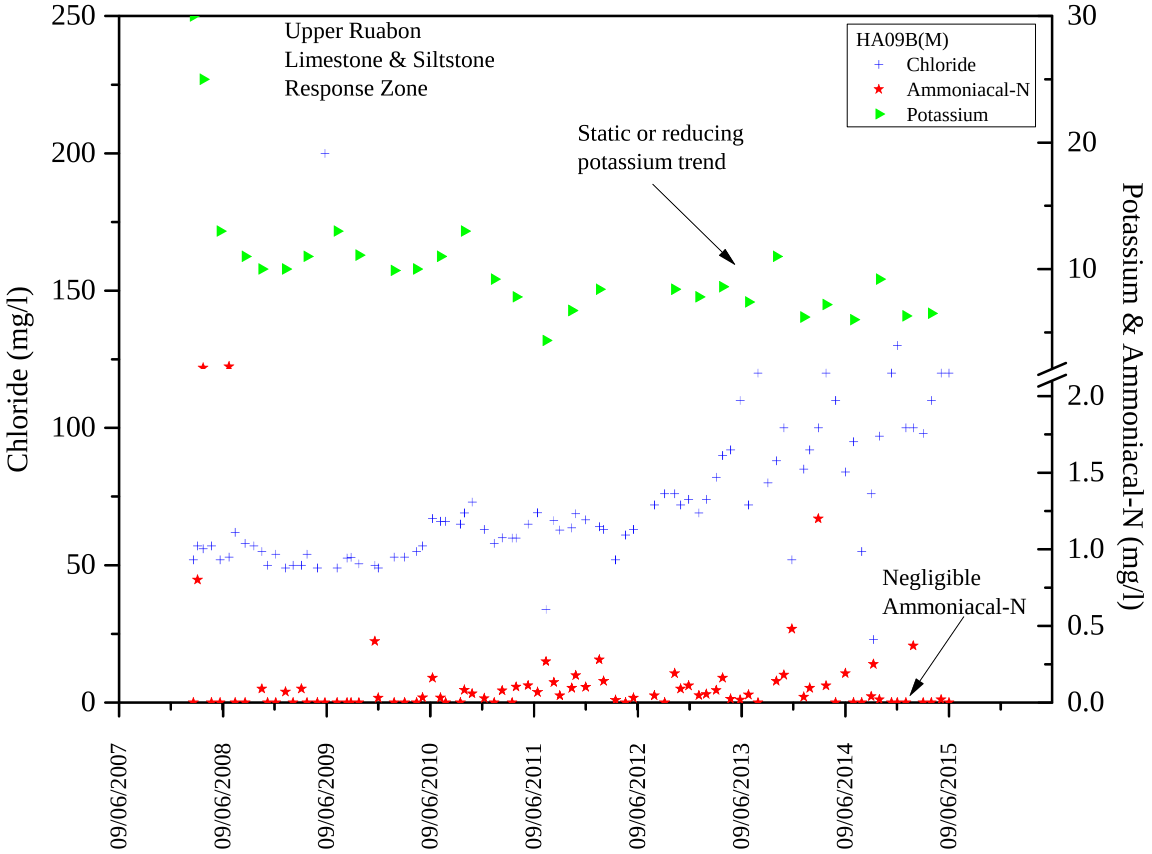
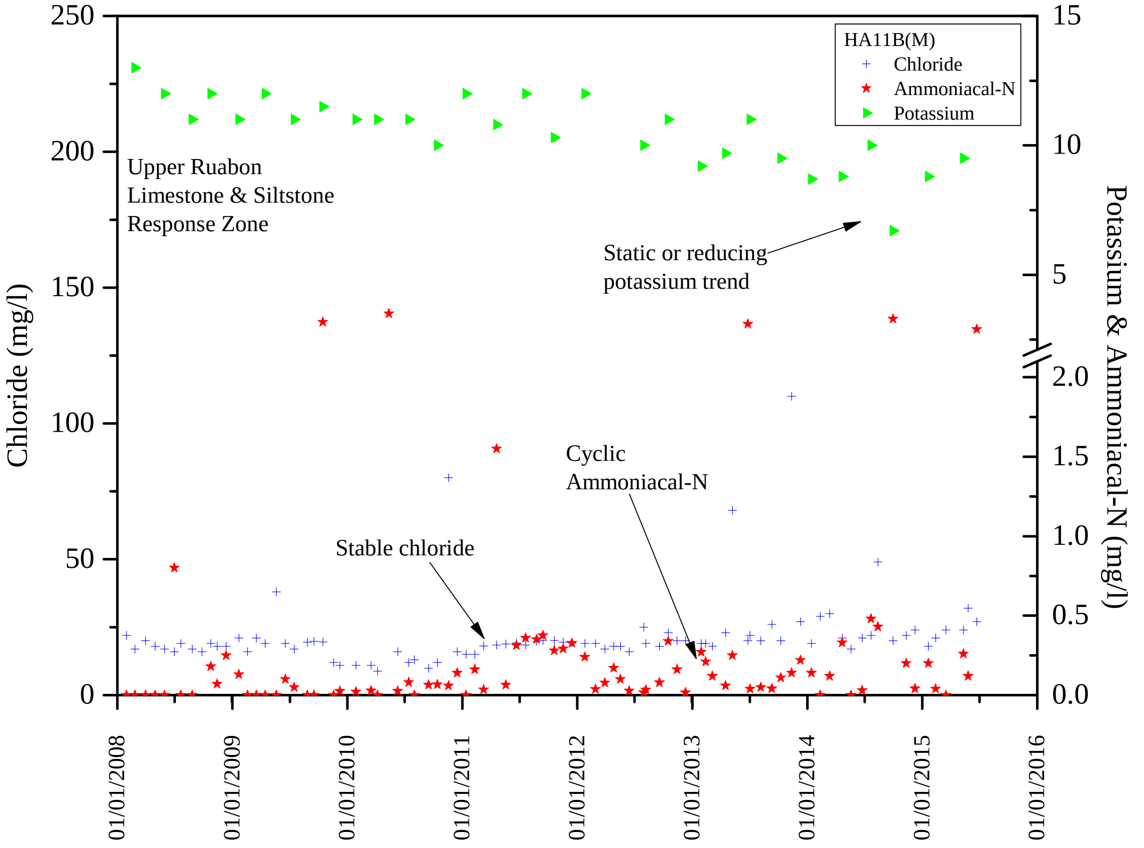


Figure 19 Primary Leachate Indicators at BH11B(M) East of Cell 2



Priority Metals

Groundwater chemistry (Table 5) has been reviewed regularly as part of annual monitoring reviews and these reviews demonstrate a low to negligible priority metal content.

The hazardous metals are not been present within the groundwater, although detection limits do vary from

Cadmium	<0.1 - <0.5μg/l; and
Mercury	<0.1 - <0.2μg/l

Similarly the majority of the non-hazardous metals are also consistently below detection limits at

Chromium	<10μg/l, compared to a DWS of 50μg/l
Copper	<5μg/l, compared to a DWS of 2,000mg/l
Nickel	<10μg/l, compared to a DWS of 20μg/l
Lead	<10μg/l, compared to a DWS of 10μg/l.

Zinc has been detected within the groundwater, although recent concentrations are typically at or approximating to the 0.01mg/l detection limit, except for three anomalies identified in 2014 at

- HA01B(B) at 0.19mg/l
- HA01B(M) at 0.1mg/l; and
- HA12A(M) at 0.85mg/l.

The observed zinc concentrations are however below both the 1mg/l Permit Limit, as well as the 5mg/l DWS. Zinc itself is however a metal which readily substitutes into the structures of the redox sensitive iron and manganese minerals. Therefore, unless the reported maximum concentrations are analytical interferences (for example from the significant suspended sediment content which can exceed 5,000mg/l) the most likely cause is mineral solution-dissolution cycles.

The Extractable Petroleum Hydrocarbons (EPH) test is undertaken on a quarterly basis and is the only screen to return non-below detection limit results. However, the quarterly screens appear to identify a correlation with the date that the samples were sent to the laboratory rather than a particular location. For example EPH was reported during the early April (08/04/15) sampling during 2015 and was found at all locations tested to the east and west of the site, including those where EPH was not reported in the previous and following quarter (Table 6).

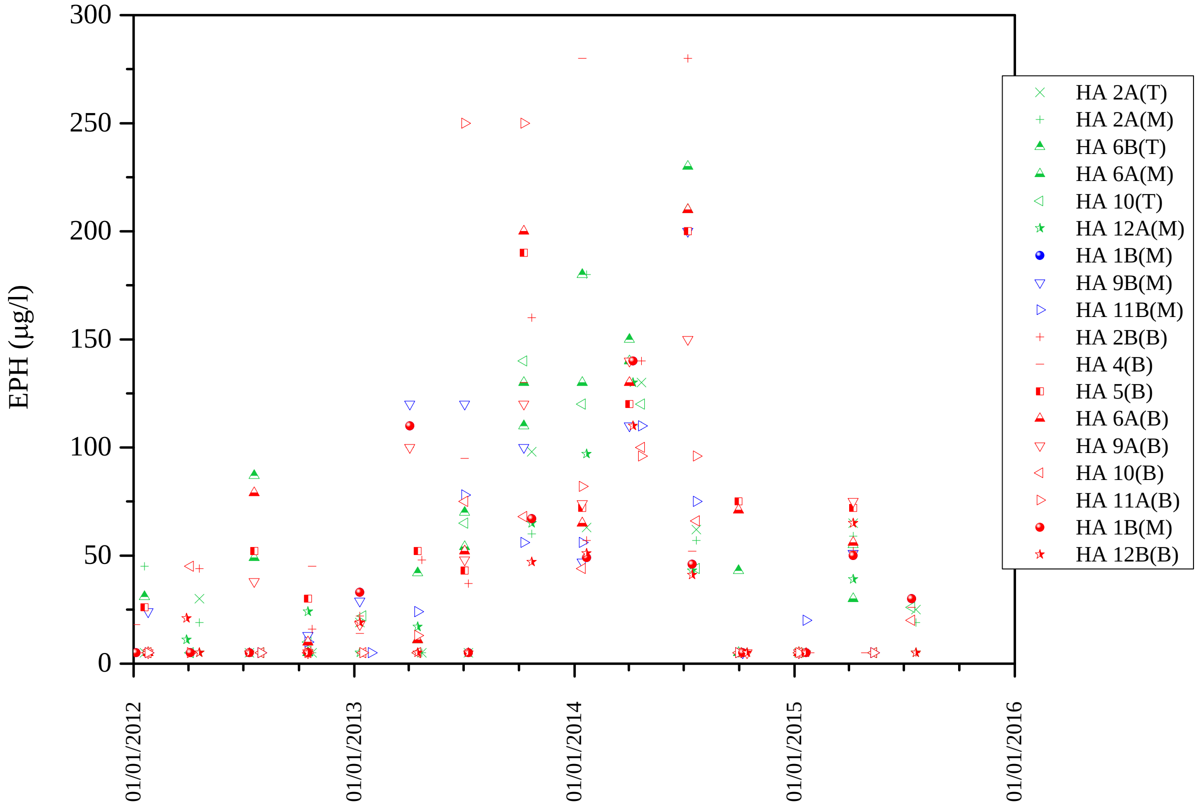
Such an affect is due to the nature of the test which is not specific to petroleum hydrocarbons and it is apparent there has been significant matrix interference resulting in flawed results, which are probably representative of natural organic matter within the groundwater and any sediment/ soil organic matter included within the sample. This misreporting / analytical interference was recently most apparent from mid-2013 to mid-2014 (Figure 20).

It is therefore considered that the EPH test is an inappropriate test for interpreting groundwater quality due to the temporal variability and ubiquitous distribution when reported. It is therefore recommended that EPH testing is discontinued for water samples.

Table 6 Groundwater EPH (2015 Quarterly Screens)

	Q1			Q2				Q3	
	08-Jan	20-Jan	27-Jan	08-Apr	22-Apr	28-Apr	12-May	14-Jul	21-Jul
East	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l
HA 2A(M)	<10			59					19
HA 2A(T)	<10			65					25
HA 2B(B)	<10			52					<10
HA 4(B)			<10			<10		26	
HA 5(B)	<10			72					
HA 6A(B)	<10			56					
HA 6A(M)	<10			30					
HA 6B(T)	<10			55					
West									
HA 1B(B)		43		52				23	
HA 1B(M)		<10		50				30	
HA 11A(B)	<10						<10		
HA 11B(M)		20					<10		
HA 10(B)	<10						<10	20	
HA 10(T)	<10						<10	26	
HA 9A(B)	<10			75					
HA 9B(M)	<10			51					
Off-site									
HA 12A(M)		<10		39					<10
HA 12B(B)		<10		65					<10

Figure 20 Extractable Organic Matter (as EPH) 2012 - 2015



4.3 Comparison with Permit Limits

Permit Limits are set for ammoniacal-N, chloride, chromium, copper, lead, nickel and zinc in groundwater monitoring locations to the east of the site (Table 7).

Table 7 Groundwater Monitoring Permit Limit Comparison (2011 - Jul 2015)

Borehole	Year	NH_4-N		Cl		Cr	Cu	Pb	Ni	Zn
		Ave	Max	Ave	Max	Max	Max	Max	Max	Max
		mg/l		mg/l		mg/l	mg/l	mg/l	mg/l	mg/l
Permit Limit			**2**		**200**	**0.05**	**1**	**0.042**	**0.05**	**1**
HA01A(T)		Dry								
HA01B(B)	2011	0.55	0.96	57	113	0.021	0.001	0.0001	0.004	0.0008
	2012	0.65	1.00	79	110	<0.01	<0.005	<0.01	<0.01	<0.01
	2013	0.51	0.75	74	92	<0.01	<0.005	<0.01	<0.01	0.03
	2014	0.64	1.20	85	100	<0.01	<0.005	<0.01	<0.01	0.19
	2015	0.47	0.68	77	84	<0.01	<0.005	<0.01	<0.01	0.01
HA09A(B)	2011	0.48	0.86	47	58	0.013	0.001	0.0002	0.003	<0.0004
	2012	0.49	2.00	41	51	<0.01	<0.010	<0.01	<0.01	<0.01
	2013	0.32	0.73	50	100	<0.01	<0.005	<0.01	<0.01	0.03
	2014	0.15	0.31	42	48	<0.01	<0.005	<0.01	<0.01	<0.01
	2015	0.14	0.19	43	46	<0.01	<0.005	<0.01	<0.01	<0.01
HA11A(B))	2011	0.48	0.80	52	55	0.025	0.007	0.0001	0.004	0.0007
	2012	0.66	1.60	53	58	<0.01	<0.010	<0.01	<0.01	<0.01
	2013	0.44	0.86	58	63	<0.01	0.008	<0.01	<0.01	0.02
	2014	0.19	0.57	68	76	<0.01	<0.005	<0.01	<0.01	0.03
	2015	0.30	0.74	75	83	<0.01	<0.005	<0.01	<0.01	<0.01
Permit Limit			**4**		**200**	**0.05**	**1**	**0.042**	**0.05**	**1**
HA01B(M)	2011	0.24	0.41	52	61	0.028	0.002	0.00002	0.004	0.001
	2012	0.49	2.8	78	110	<0.01	<0.010	<0.01	<0.01	<0.01
	2013	0.36	1.00	84	130	<0.01	<0.005	<0.01	<0.01	<0.01
	2014	0.16	0.24	89	120	<0.01	<0.005	<0.01	<0.01	0.10
	2015	0.36	0.96	77	84	<0.01	<0.005	<0.01	<0.01	<0.01
HA09B(M)	2011	0.10	0.27	61	69	0.021	0.005	0.0002	0.004	0.0007
	2012	0.09	0.28	67	76	<0.01	<0.010	<0.01	<0.01	<0.01
	2013	0.11	0.48	86	120	<0.01	<0.005	<0.01	<0.01	0.02
	2014	0.16	1.20	91	130	<0.01	<0.005	<0.01	<0.01	0.02
	2015	0.20	0.37	108	120	<0.01	<0.005	<0.01	<0.01	<0.01
Permit Limit			**4**		**200**	**0.05**	**1**	**0.15**	**0.1**	**1**
HA11B(M)	2011	0.34	1.55	18	200	0.031	<0.0009	0.000 09	<0.003	0.005
	2012	0.11	0.34	19	25	<0.01	<0.010	<0.01	<0.01	0.13
	2013	0.38	3.10	33	110	<0.01	<0.005	<0.01	<0.01	0.02
	2014	0.46	3.30	25	49	<0.01	<0.005	<0.01	<0.01	0.04
	2015	0.70	2.90	24	32	<0.01	<0.005	<0.01	<0.01	<0.01
Permit Limit			**2**		**200**	**0.05**	**1**	**0.15**	**0.2**	**1**
HA09A(T)		Dry								
Permit Limit			**2**		**200**	**0.05**	**1**	**0.15**	**0.15**	**1**
HA11B(T)		Dry								
Permit Limit			**2**		**450**	**0.05**	**1**	**0.042**	**0.05**	**1**
HA12A(M)	2012	0.09	0.35	232	360	<0.01	<0.010	<0.01	<0.01	<0.01
	2013	0.08	0.47	228	320	<0.01	<0.005	<0.01	<0.01	0.09
	2014	0.10	0.59	183	250	<0.01	<0.005	<0.01	<0.01	0.85
	2015	0.08	0.23	230	300	<0.01	<0.005	<0.01	<0.01	<0.01
HA12B(B)	2012	0.74	1.20	1,320	1,600	<0.01	<0.010	<0.01	<0.01	<0.01
	2013	0.49	1.00	1,023	1,200	<0.01	<0.005	<0.01	<0.01	<0.01
	2014	0.32	1.10	1,147	1,400	<0.01	<0.005	<0.01	<0.01	<0.01
	2015	0.20	0.44	1,229	1,500	<0.01	<0.005	<0.01	<0.01	<0.01

Shaded cells exceed Permit Limit

There has only been one location where a Permit Limit has been exceeded over the recent date range, namely HA12B(B), where the chloride Permit Limit has been exceeded (Table 7). However, this exceedance as discussed above is not consistent with landfill leachate migration, as the monitoring locations directly adjacent to the site have not been affected, and there are not any association with other leachate determinands which would be expected given that at HA 12B(B), chloride is at 50% of the sustained leachate chloride concentration.

Such an impact, over such a short timescale could only occur if there was a direct mixing with landfill leachate, in which case both potassium and ammoniacal-N would be expected at concentrations in the order of 300 and 750mg/l respectively. Consequently it is considered that the source of the chloride at the A483 junction monitoring locations (*i.e.* at borehole HA12), is unrelated and independent of the Hafod landfill operations.

A new borehole (BH HA12C (B), Drawing HAF128) has therefore been installed in November 2015 at the eastern perimeter of the site and following a 6-month period of comparative monitoring it is proposed that, this new edge of site monitoring point replaces the off-site monitoring points. The proximity to the site will allow the new installation to act as a more representative monitoring point which is less likely to be influenced by off-site effects.

The statistics for ammoniacal-N at BH11B(M) are not considered representative of the actual steady-state cyclic pattern due to a series of outlier values ay ~3mg/l, whilst, there is a sustained cyclic trend at <0.02 - 0.5mg/l, which is considered to represent the underlying biological processes. An interpretation confirmed by the low associated chloride concentrations from 10 - 32mg/l.

The priority metals are consistently reported as below detection limits with no recent evidence of sustained increasing trends or even presence within the groundwater.

4.4 Summary

The groundwater within the vicinity of the Hafod landfill site is unaffected by the landfill operations due to a combination of:

- Maintaining landfill leachate below groundwater, resulting in a confining inwards hydraulic gradient from water bearing strata.
- The physical separation of groundwater from landfilled waste by the engineered containment measures.

There are no underlying groundwater receptors to be a potential risk target and the host mudstones are not water bearing, as confirmed by site observations of water within the basal groundwater management system, where there has not been the accumulation of groundwater or leachate seepages.

The groundwater quality monitored as part of the routine monitoring schedule, which is based on calcium sulphate and bicarbonate solution is therefore considered as representative of the natural variation of the background geochemistry in the site's location.

With regards to the non-representative data provided by BH HA12BB, proposals have been agreed with NRW for the installation of a replacement borehole with a location between HA01 and HA11 (BH HA12C (B) Drawing HAF128). An edge of site replacement will reduce the potential for off-site influences.

5. CONCEPTUAL SITE MODEL

A conceptual model has been constructed for the site, based on the relationship:

Source → Pathway → Receptor

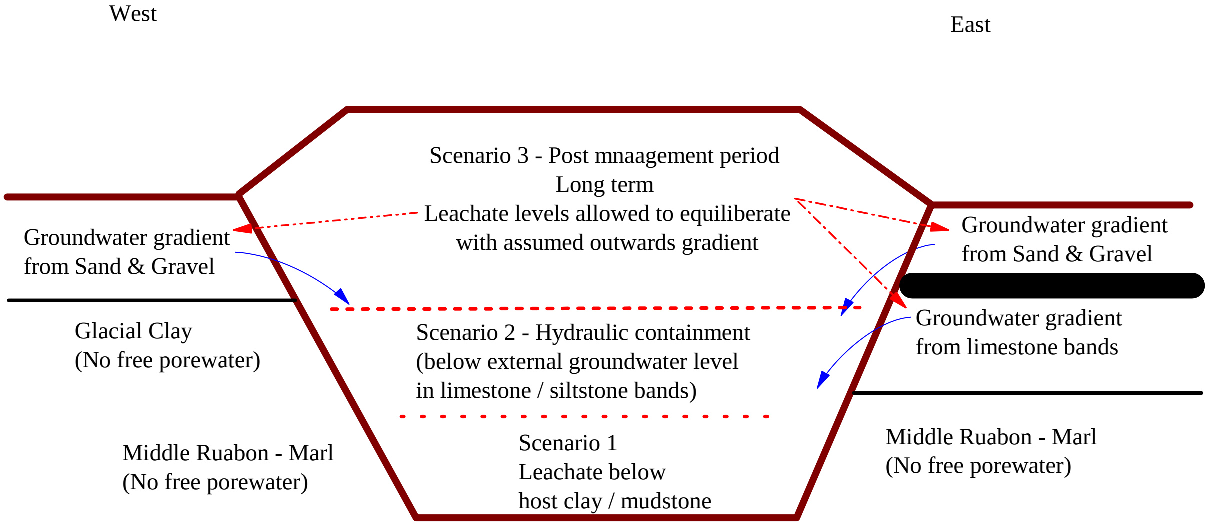
Where

- The source is leachate within the landfill
- The Pathway is the engineered containment; and
- The Receptor is saturated strata outside of the site

Three scenarios can be developed, dependent on leachate height (Figure 21), namely:

1. Current Position when leachate levels are maintained below the top of the clay geological barrier;
2. Intermediate term period where leachate levels are managed below ground water levels; and
3. Post-aftercare period when leachate levels are no longer actively managed.

Figure 21 Schematic Conceptual Model Scenarios



The previous risk assessments translated the conceptual scenarios into four assessment source- receptor models, namely:

Post Closure / Aftercare Period - Modelled using Hydraulic Containment Model

- Scenario B Diffusive flux of leachate constituents through the sidewall liner into the limestone bands
- Scenario C Diffusive flux of leachate constituents through the sidewall liner into the sand and gravel

Post-Aftercare Period (Long term) - Modelled using LandSim

- Scenario D Advective flux of leachate through the engineered sidewall liner into the limestone bands

- Scenario E Advective flux of leachate through the engineered sidewall liner into the sand and gravel

Operational Period
A fifth assessment (Scenario A) was also considered, namely seepage through the basal liner and into the groundwater management layer. This scenario was not undertaken to assess the impact on an at risk underlying groundwater system as an underlying groundwater management system does not exist. Instead, this scenario was modelled to assess whether leachate seepage into the groundwater management system after mixing with the sidewall drainage waters could cause pollution when discharged from the site.

Such a process is a short term scenario, during the early operational stage of a cell's life, as groundwater management is only required for the period when there is an insufficient thickness of waste to overcome basal heave. Site management have reported that there is insufficient groundwater accumulation within the basal groundwater management system to require active management (although relatively high volumes continue to be produced from both the eastern and western sidewall drainage systems). Therefore the scenario of seepage through the basal liner is no longer considered as a relevant risk-pathway.

A direct risk to an underlying groundwater system was not considered a risk pathway during the previous assessments as there is not a source-pathway-receptor relationship when leachate is maintained below the top of the geological barrier.

6. HYDROGEOLOGICAL RISK ASSESSMENT

6.1 Justification for Modelling Approach and Software

Complex risk-assessments are numerical quantitative numerical assessments undertaken when there is a reasonable concern that pollution could occur if managed controls are not implemented. The assessments can also be used to define risk-based passive and active management controls necessary to prevent pollution.

The approach taken within the risk assessments was based on relating the scenario to a modelling programme design and distributed by the Environment Agency, namely:

- The Hydraulic Containment Model, where leachate is below groundwater levels; and
- LandSim for leachate heights above the external groundwater level

Hydraulic Containment Model
The Environment Agency has produced a model calculation programme to assess contaminant fluxes from hydraulically contained landfills[6], which is supported by a technical review[7]. This model was produced because mass transport models, including programmes such as LandSim which are based on substance migration which is proportional to the hydraulic gradient. Under hydraulic containment this flux is into the landfill site and the hydraulic models would return a zero value.

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[6] Environment Agency (2004) Contaminant fluxes from hydraulic containment landfills spreadsheet v1.0 User Manual. Science Report SC0310/SR

[7] Environment Agency (2004) Contaminant fluxes from hydraulic containment landfills spreadsheet - a review. Science Report SC0310/SR

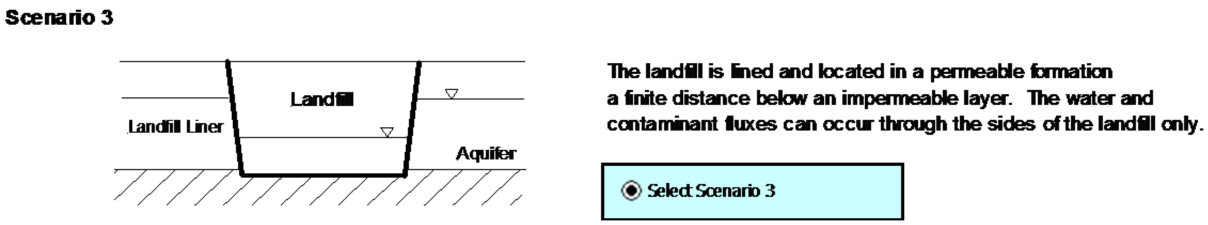
However, chemicals will diffuse across a concentration gradient even when against the hydraulic flux, albeit at a significantly lower rate than occurs under a hydraulic gradient when there is the physical movement of dissolved chemicals with the hydraulic flow. The hydraulic containment model has been produced to assess the chemical diffusion flux through the sides and / or base of a landfill in the context of how diffusion is affected by the inwards hydraulic gradient and landfill liner properties.

The site's operating philosophy is based on artificially creating an inwards hydraulic gradient by active leachate management, *i.e.* the maintenance of a leachate head at or below the external groundwater levels. Therefore the risk process requires that the chemical diffusion potential from the landfill to the environment is considered to ensure that an appropriate risk-based inwards gradient can be defined to prevent pollution.

The Hydraulic Containment Model (HCM) is a steady-state model, which calculates the diffusion of contaminants through a geological strata or liner that does not take leachate depletion into account. Therefore, unlike models such as LandSim, the effects of the source depletion as contaminants are removed, such as by abstraction, are not considered within the model conclusions and any conclusions drawn are therefore conservative with regards to the intermediate and long term.

Given that the site is located above a significant thickness of mudstone and the greatest risk is considered to be associated with the integrity of the sidewall liner, then Hydraulic Containment Model Scenario 3 (Figure 22) is considered as the most appropriate scenario

Figure 22 Hydraulic Containment Model Scenario 3 - Sidewall Diffusion



Scenario 3

The landfill is lined and located in a permeable formation a finite distance below an impermeable layer. The water and contaminant fluxes can occur through the sides of the landfill only.

● Select Scenario 3

LandSim

The LandSim model[8] was developed on behalf of the Environment Agency by Golder Associates is the preferred model for assessing risks to groundwater from landfill sites by each of the UK's Environment Agency bodies and is the preferred tool for modelling above groundwater landfill sites. The LandSim model is a Monte Carlo simulator, which is a probabilistic simulator to assess contaminant migration from a source through a barrier system which underlies the potential polluting source, vertically through an unsaturated zone beneath the barrier, and a saturated pathway before entering an aquifer.

The Monte Carlo Simulator allows for a stochastic approach to be taken for the model. Stochastic models allow a range of values to be input for each parameter. The model then selects a value for each parameter when running a simulation. Thus the model overcomes difficulties associated with deterministic models which take a single value for each parameter when a series of end member scenarios are run without understanding how each parameter interacts or their relative importance.

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[8] Golder Associates (UK) Ltd (2003) LandSim. Landfill Performance Simulation by Monte Carlo Method. *Environment Agency R&D Publication 120*

The model also performs multiple simulation runs and the simulation programme compiles the results as a statistical probability of a particular result occurring. When the results are statistically combined, the likelihood of each of the 'worst-case' parameters occurring simultaneously can be compared with the general case which is actually expected to happen. The impact of each of these cases and that of intervening probabilities can then be compared with relevant water quality standards to determine if the risk is acceptable.

The model also predicts timescales that any potential impact is likely to occur over. This includes factoring in whole lifecycle factors such as active or passive engineered controls and the polluting lifespan of the contaminant source.

With regards to Hafod, the LandSim model is only applicable for the area of the sidewall that is not directly underlain by mudstone; hence the potential risk pathway is limited to the zone above the limestones and the Sand and Gravel.

6.2 Model Parameterisation

There is not a substantive change to the site compared to the previous (2010) assessment as there has only been limited development of the site, namely:

- The construction of Cells 3 and 4
- Disposal operations within Cell 3;
- The continued accumulation of leachate quality and level data

Therefore the majority of the previously assumed parameters for the receptors within the modelled assessments remain valid.

Source Concentration

The key determinand concentrations used within the previous assessments have been reproduced in context with the recent monitoring data (Table 8). This comparison differs from that in Table 3, which compares the recent data in the context of actual monitoring data immediately prior to the 2010 HRA review.

The monitoring data demonstrates that the leachate chemistry is within the range previously modelled. The most significant difference is with ammoniacal-N, where the current data indicates an average concentration of 2,100mg/l, compared to a previously assumed 1,600mg/l, even though the recent maximum concentration of 3,200mg/l is below that of the previously assumed 3,640mg/l.

Although there is a similar type of distribution for chloride, chromium and nickel, in which the recent average concentration is above that previously modelled, the increase in the average concentration is not significant when compared to maximum concentration modelled previously. Consequently there is no change in the risk profile for these substances compared to that previously assumed followed the 2003 and 2010 HRA reviews.

This source term was used for all scenarios during both hydraulic containment and post-aftercare scenarios. The applicability to the hydraulic containment scenarios is due to the presumption that there has been insufficient time for leachate to deplete at the start of the aftercare period (*i.e.* immediately after closure). However, this assumption cannot be made for the post-aftercare period when the leachate will have depleted in strength to a point where active management is no longer required.

Table 8 Comparison Recent Monitoring Data with Previously Modelled Source Terms

Determinand		Original HRA	2010 HRA	Current Leachate Quality
Ammoniacal-N	mg/l	1,010 - 1,674 - 2,100	575 - 1,592 - 3,640	970 - 2,100 - 3,200
Chloride	mg/l	300 - 909 - 1,720	920 - 1,884 - 7,760	2,000 - 2,600 - 4,280
Arsenic	µg/l	5 - 219 - 290	No data (Pb)	Not analysed
Lead	µg/l	Not modelled	300 - 440 - 1,020	<10 - 40
Cadmium	µg/l	2.5 - 10.1 - 105	0.5 - 2.6 - 105	<0.1 - <0.5 - <1
Mercury	µg/l	0.04 - 0.09 - 1.95	0.05 - 0.1 - 1.95	<0.1 - <0.3 - <0.5
Chromium	µg/l	159 - 438 - 702	5 - 230 - 1,750	<10 - 355 - 607
Copper	µg/l	5 - 44 - 59	5 - 120 - 1,130	<5 - <10 - 310
Nickel	µg/l	25 - 139 - 249	5 - 300 - 2,210	10 - 337 - 470
Mecoprop	µg/l	0.05 - 40 - 100	0.05 - 11 - 140	<0.02 - <0.02- 121
Naphthalene	µg/l	0.05 - 10 - 100	0.05 - 0.5 - 42	<0.001
PCE	µg/l	0.05 - 10 - 100	No Data	<0.001
Phenol	µg/l	0.05 - 10 - 100	6 - 60 - 208,000	<0.1

Minimum - Most Likely - Maximum concentration

Leachate Level

The correlation of the leachate level to those presented in previous assessments is more difficult for the Hafod landfill site than other sites as in the majority of cases the correlation is between the leachate height acting on the base of the site and the previously modelled height. However, at Hafod, the leachate height acting on the base of the site does not present as a risk-criteria.

Difficulties are also encountered from the difference between the height of foam/perched leachate and that provided by transducers in previous investigations. Retro-drilled wells and borehole investigation indicate that leachate heights are <4m above the base of the site and hence the leachate is confined within the surrounding mudstone geological barrier and is physically below the base of the limestone bands. As long as leachate is maintained below the base of the limestone, there is not a risk of pollution from the site.

However, for sensitivity purposes, as the leachate foam has approximated to the external groundwater level within the adjacent Limestone bands (and below the Sand and Gravel water levels), then it is considered appropriate to re-model ammoniacal-N at the current most likely concentration and foam height as average concentrations have increased above that previously assumed. Therefore the hydraulic containment model for the most sensitive receptor (*i.e.* the limestone) has been reconsidered within this assessment.

The model parameters are reproduced from the 2010 HRA as Table 9, with the following parameter updates:

1) increase in diffusion face from 89mAOD to 84mAOD to increase diffusive flux surface area
2) Minimise inwards gradient to elevation of groundwater at BH09 (*i.e.* reduced from 102.5mAOD to 91mAOD)
3) Modelled foam height at 90mAOD(reduced from 101mAOD)
4) An increase in the modelled ammoniacal-N concentration from 1,490mg/l to 3,200mg/l (the recent maximum concentration).

Table 9 Hydraulic Containment Model to Limestone Receptor

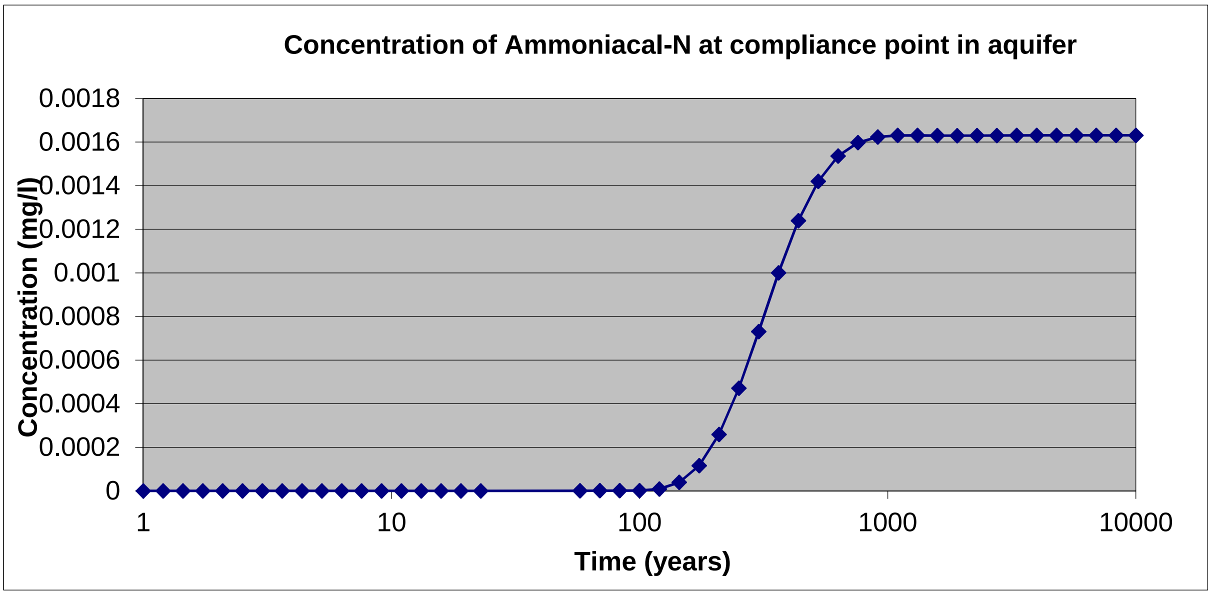
Hafod Landfill Site		5 October 2015	
CONCEPTUAL MODEL AND LANDFILL CONSTRUCTION			
Conceptual model of landfill construction	CM	3	-
Is a geomembrane present?	GM_opt	No	-
Basal width perpendicular to groundwater flow	Width_LF	250	m
Basal length parallel to groundwater flow	Length_LF	100	m
Basal area	Base_Area	25000	m^2
Elevation of base of landfill	LFbase_elev	72	maOD
Elevation of base of aquifer	Aqbound_elev	84	maOD
Leachate head inside landfill	Head_inLF	90	maOD
Groundwater head outside landfill	Head_outLF	91	maOD
Area of liner below the water table	Area_contact	8400	m^2
CONTAMINANT PARAMETERS			
Contaminant name	Cont_Nme	Ammoniacal-N	-
Contaminant type	Cont_Type	Inorganic	-
Contaminant classification	Cont_Class	List II	-
Concentration in landfill leachate	Conc_LF	3,200	mg/l
Free water diffusion coefficient	Dw_cl	1.96E-09	m^2/s
Partition coefficient in clay	Kd_cl	1.25	l/kg
Retardation factor in clay	R_cl	22.42	-
Half life in clay (0 for no decay)	thalf_cl	0	days
Decay in sorbed phase?	Decay_sorb	No	-
Decay constant in clay	Decay_cl	0	1/s
MINERAL BARRIER / LINER			
Thickness of mineral liner	thick_clbr	1.075	m
Hydraulic conductivity	k_cl	1.93E-10	m/s
Average pore radius	pore_radius	1.00E-05	m
Effective porosity	n	0.105	-
Dry bulk density	rho	1800	kg/m^3
Tortuosity	tau_cl	10	-
STEADY STATE DILUTION			
Hydraulic gradient in the aquifer	aq_I	0.0013	-
Hydraulic conductivity of the aquifer	k_aq	5.50E-05	m/s
Downgradient distance of compliance point from landfill	dist_cp	50	m
Mixing width	Mix_W	250	m
Mixing depth	Mix_D	7	m
Dilution flow in aquifer downstream to the landfill	aq_Q	0.000125125	m^3/s
CONTAMINANT AND WATER FLUXES			
Groundwater flux into landfill		1.50809E-06	m3/s
Maximum contaminant concentration at compliance point at tmax	C_comp	0.001630993	mg/l
CHART PARAMETERS			
Minimum axis display	tmin	1	years
Maximum axis display	tmax	1.00E+04	years

6.3 Emissions to Groundwater

The hydraulic containment model predicts that at current leachate concentrations and an elevation equivalent to the foam height, there is no risk to the external groundwater as travel times are greater than a century and the resulting groundwater concentration would be at least an order of magnitude below discernible concentrations (Figure 23).

Consequently an impact on the groundwater system is not expected to occur, even if the perched leachate / foam height is representative of actual leachate heights.

Figure 23 **Hydraulic Containment Model Predicted Ammoniacal-N Concnetration in Limestone**



6.4 Modelling Conclusion

Hafod Landfill Site has been constructed and operated to within the parameters previously assessed, albeit that average concentrations for some parameters are higher than previously assumed, maximum concentrations have not been exceeded.

Therefore there is not a requirement to remodel the site within this assessment. Notwithstanding this, a re-assessment of the most sensitive parameter, namely ammoniacal-N, has been undertaken. The conclusion of this assessment is that there is no risk to the limestone bands above the mudstone from leachate, even if leachate levels were to be at the height of the foam recorded within the monitoring wells.

7. REVIEW OF TECHNICAL PRECAUTIONS

The site was developed after the introduction of the Landfill and Groundwater Directives, hence the site can conclusively be determined as Groundwater Directive compliant.

These technical precautions can be summarised as

- A sloped surface designed to shed incidental rainfall
- A vegetated and soil restored surface designed to protect he underlying cap
- An engineered cap designed to minimise infiltration
- Sidewall drainage designed to reduce the lateral groundwater pressure acting on the upper sidewalls of the site

- An artificial geological barrier abutting the sidewall drainage system, adjacent to permeable strata;
- A mineral sidewall liner overlying the sidewall artificial geological barrier
- A basal drainage layer with abstraction chambers
- A basal slope designed to facilitate leachate collection
- A mineral liner
- An *in-situ* geological barrier, provided by the host mudstone bedrock.

Leachate is managed at the site by active abstraction; however, some of the abstraction chambers have been compromised by silt or have deformed (and are being replaced). Notwithstanding this, leachate levels are considered to be below the top of the surrounding mudstone strata, even though there is foaming or perched leachate within monitoring points.

The site is permitted with a leachate height of 2m above the base of each cell. However, it is considered that this height is inappropriate for a landfill with no underlying receptor and no evidence of seepage into the underlying drainage layer.

It is proposed that whilst groundwater management is in progress and there is the potential for spillage into the undeveloped future operational areas of the site, that leachate levels should be based on two criteria for the operational and non-operational cells.

- For the operational cell in which leachate is retained below a terminal bund (*i.e.* currently Cell 4), that leachate levels are maintained at 1m below the top of the terminal bund; and
- For cells without a terminal bund into the undeveloped cells, leachate levels should be maintained at 1m below the external groundwater level within the Limestone beds. At present, this equates to an elevation of 89.6mAOD (*i.e.* 1m below the 90.6mAOD minimum reported for BH HA09B(M) (Figure 13).

This scenario can continue until the last cell is engineered and there is no terminal cell within the site. At this point, leachate levels should be managed solely based on the groundwater height in the adjacent limestone strata. Once the site develops to the stage where groundwater management is no longer required, then the leachate management philosophy should be reassessed and based on groundwater levels at that point in time.

Leachate is tankered from site for treatment, whilst the intercepted groundwater and incidental rainfall into the non-operational areas is allowed to settle within a pair of lagoons and then discharged from the site. Limits are set for this discharged solution, with the primary objective of ensuring that leachate seepage into the basal groundwater management system does not pollute the receiving surface water.

Although there is the provision for managing groundwater within the Etruria Marl, this is an unnecessary requirement as the mudstone does not contain sufficient groundwater to warrant active management. Consequently the potential for basal seepage to impact surface water is expected to continue to be negligible.

Notwithstanding the above, it is considered appropriate to continue to monitor the surface discharge from the site to ensure that leachate either from over-topping the terminal bund at the edge of the active cell or spillages of the transfer infrastructure do not cause pollution.

8. REQUISITE SURVELLIANCE

There is ongoing surveillance of the quantity and quality of leachate within the site as well as of the groundwater quality in perimeter wells and the surface waters discharged from the site.

There are three proposed changes to the monitoring schedule. The first is to relate leachate levels to the potential for over-topping the terminal bund and the groundwater level within the limestone units.

The second change is to replace the BH HA12B(B) location at the edge of the A483 with a replacement monitoring point directly adjacent to the north eastern perimeter (BH HA12C(B). The location at the A483 junction, some 260m from the edge of the site is at a distance greater than that recommended within LFTGN02[9], which states that groundwater monitoring points should be "no further than 100m from the waste margin". The monitoring points adjacent to the A483 are outside of the influence of Hafod landfill site and patently influenced by off-site sources and hence the use of Permit Limits for this location is inappropriate.

It is however proposed that the BH HA12B(B) monitoring point is replaced by a new installation located between BH01 and BH11 adjacent to the edge of the site. A new monitoring point (HA12C(B)) has been installed during November 2015 which will provide information with a greater potential to evaluate any influence of the landfill on the groundwater system. A 6-mopnthly programme has been agreed with NRW to undertake comparative monitoring between the existing HABH12 series and the newly installed HA12 monitoring point. A revised Permit Limit schedule will be proposed once sufficient data has been collected and evaluated.

The proposed leachate monitoring schedule is presented within Table 10. The groundwater monitoring schedule is presented in Table 11, with Permit Limits shown in Table 12.

The surface water monitoring schedule is presented within Table 13; however, as noted in previous annual reviews, the surface water Permit Limit schedule appears unnecessarily extended given that a primary component of the discharged water is derived from the Sand and Gravels. For example components such as calcium and sulphate are not an indicator of leachate spillages, whilst the alkalinity will not cause harm to the surface water and there is no risk-based justification for such an extended suite with Permit Limits. Further discussion is provided below.

In addition, there is not a risk based justification for monitoring SW4. This monitoring point is a second monitoring point downstream of the site, and acts as a duplicate monitoring point to SW3 which is approximately 50m downstream of the site discharge points. SW4 is a further 200m downstream from SW3, and is located on the opposite side of a major trunk road (the A483). Any useful information related to the Hafod landfill would therefore be identified from monitoring at SW3, whilst at SW4 there is a greater potential for identifying road run-off (including chloride) and agricultural influences (*e.g.* ammoniacal from manure run-off) unrelated to the site activities. It is therefore considered that SW4 is an unnecessary duplication.

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[9] Environment Agency (2003) Guidance on Monitoring of Landfill Leachate, Groundwater and Surface Water. LFTGN02

Table 10 Leachate Monitoring Schedule

Monitoring Point	Parameter	Limit	Frequency
Internal Cells	Dip to leachate Leachate Height Dip to base	None set 89.65mAOD None set	Quarterly Quarterly Annually
External Cell	Dip to leachate Leachate Height Dip to base	None set 1m below terminal bund None set	Monthly Monthly Annually
1 point per cell	pH, EC, alkalinity, NH_4-N, Cl, COD, BOD, Cd, Cr, Cu, Pb, Ni, Fe, As, Mg, K, SO_4, Ca, Na, Zn, Mn	None set	Quarterly until each cell closure then annually
	Hazardous Substances	None set	Annually until each cell closure then once every four years

Table 11 Groundwater Monitoring Schedule

Monitoring Point	Parameter	Frequency
All Locations	Dip to water (m) Water Level (mAOD)	Quarterly until closure then six monthly
	NH_4-N, Cl, pH, EC	Quarterly until closure then six monthly
	alkalinity, Mg, K, SO_4, Ca, Na, Cr, Cu, Fe, Pb, Ni, Zn, Mn	6-monthly

Table 12 Groundwater Monitoring Permit Limits

Location	NH_4-N	Cl	Cr	Cu	Pb	Ni	Zn
	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
HA01A(T)	2	200	1	1	0.042	0.05	1
HA01B(B)							
HA09A(B)							
HA11A(B)							
HA01B(M)	4	200	0.05	1	0.042	0.05	1
1HA09B(M)							
HA11B(M)	4	200	0.05	1	0.15	0.1	1
HA09A(T)	2	200	0.05	1	0.15	0.2	1
HA11B(T)	2	200	0.05	1	0.15	0.15	1
HA12C (B)	New location, limits to be proposed when sufficient data available						

The surface water contains a combination of surface run-off following rainfall events and groundwater diverted from the sand and gravels or the limestone bands. This groundwater and surface water run-off would naturally discharge into the Aberderfyn, however, as there is also the potential for leachate spillage to be mixed with these waters, there is a requirement to monitor for contamination.

It is considered that the surface water monitoring schedule and the setting of Permit Limits is inappropriately complex. The monitoring schedule and the setting of Permit Limits should be based on determining if there has been an outbreak of landfill leachate which could cause harm to the receiving Aberderfyn. With regards to causing harm there are only three determinands along with suspended solids which are reasonably likely to be within the leachate at a sufficiently high concentration to cause harm after mixing with the surface water run-off.

These substances are

- ammoniacal-N, BOD and which could cause eutrophication;
- chloride which could lead to an elevated salinity; and
- suspended solids which could smother the ecology within the stream.

The above listed substances are the only potential leachate constituents which have the potential to be discernible above background concentrations. The other matrix substances are naturally present, for example the background geochemistry is dominated by a calcium bicarbonate (Figure 25) and sulphate (Figure 24) geochemistry of the area.

The majority of Permit Limit exceedances to date cannot be related to a leachate influence and occur as isolated occurrences where a wider evaluation of the data demonstrates that there is no association with other leachate constituents which would be expected to be present if the source were leachates. It is also noted that limits have been set for substances where there are no statutory or non-statutory EQS levels (*e.g.* potassium, calcium, alkalinity, COD, TOC)

The limits set for the hazardous and non-hazardous metals have never been exceeded in the past and in any case, monitoring for ammoniacal-N and chloride will provide a definitive answer as to whether there is a leachate influence on the surface water, whilst the non-hazardous and hazardous metals are only likely to be illustrative of the background fluctuation or analytical bias unrelated to an actual leachate influence.

Although it is still recommended that ammoniacal-N and chloride monitoring is continued on a routine basis, caution should still be employed as historically when spikes in concentration have been observed in Aberderfyn (Figure 26 and Figure 27), the source can be correlated to an upstream effect which occurs at a greater influence within SW1 (upstream) which then depletes towards SW3 (downstream) and SW4 (downstream).

Although non-landfill influences including winter road treatment (chloride), seasonal agricultural fertilization (*e.g.* manure spreading resulting in ammoniacal-N) and algal growth within on-site ponds (ammoniacal-N) can superficially lead to an ammoniacal-N influence conclusion, the seasonal nature of the influences and a comparison between chloride and ammoniacal-N profiles at each location can be used to distinguish landfill from non-landfill influences.

A revised monitoring schedule has therefore been proposed (Table 13), with the substances which are proposed as being removed from the schedule presented in Table 14.

Figure 24 Surface Water Sulphate

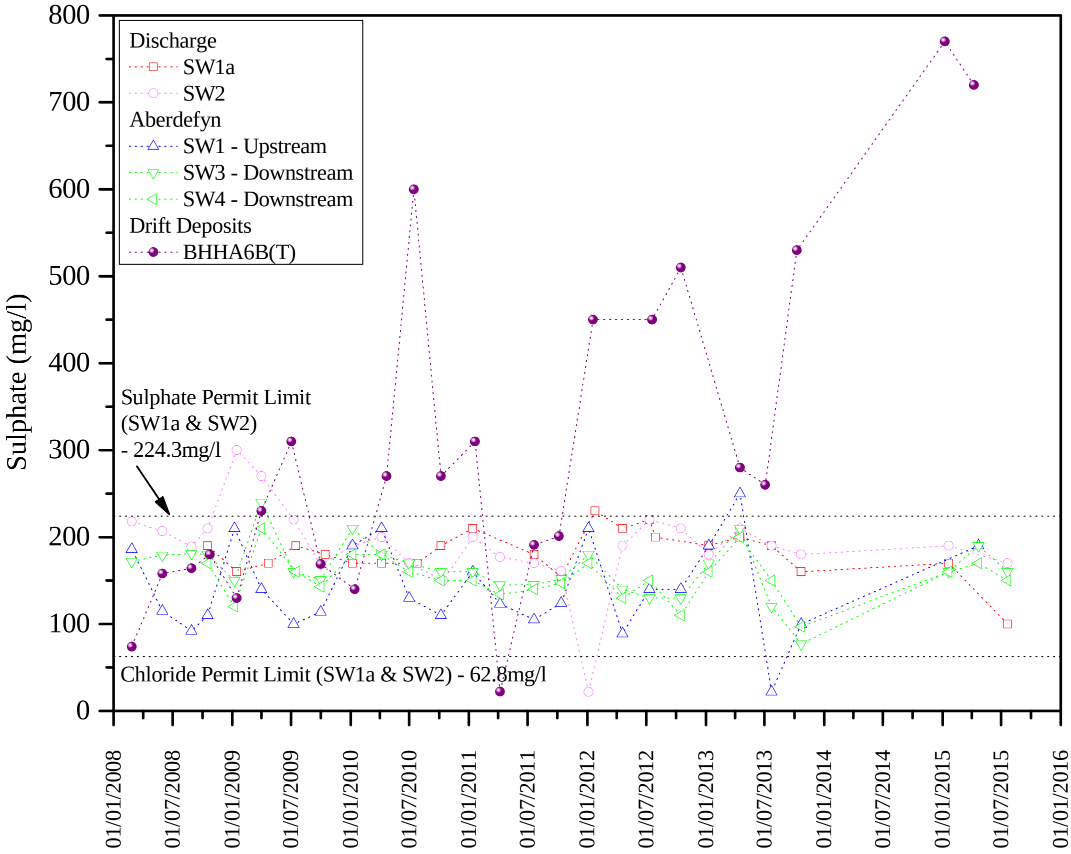


Figure 25 Surface Water Alkalinity

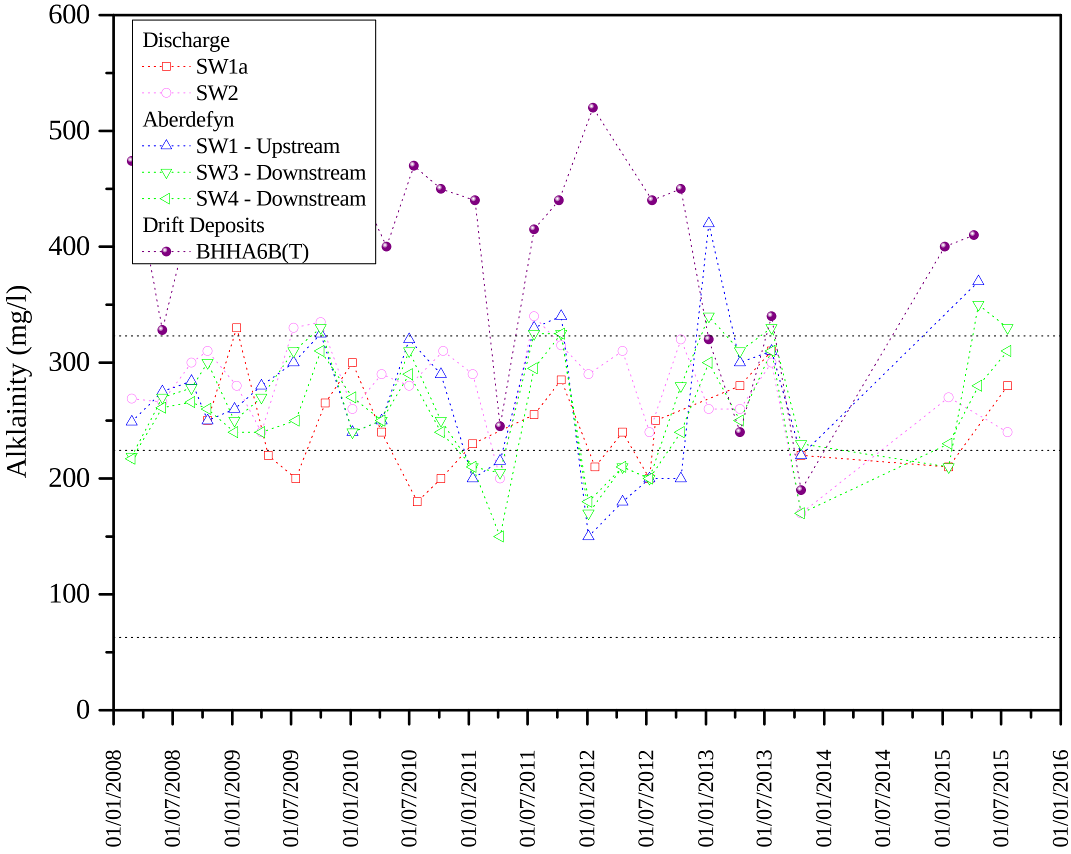


Figure 26 Surface Water Chloride

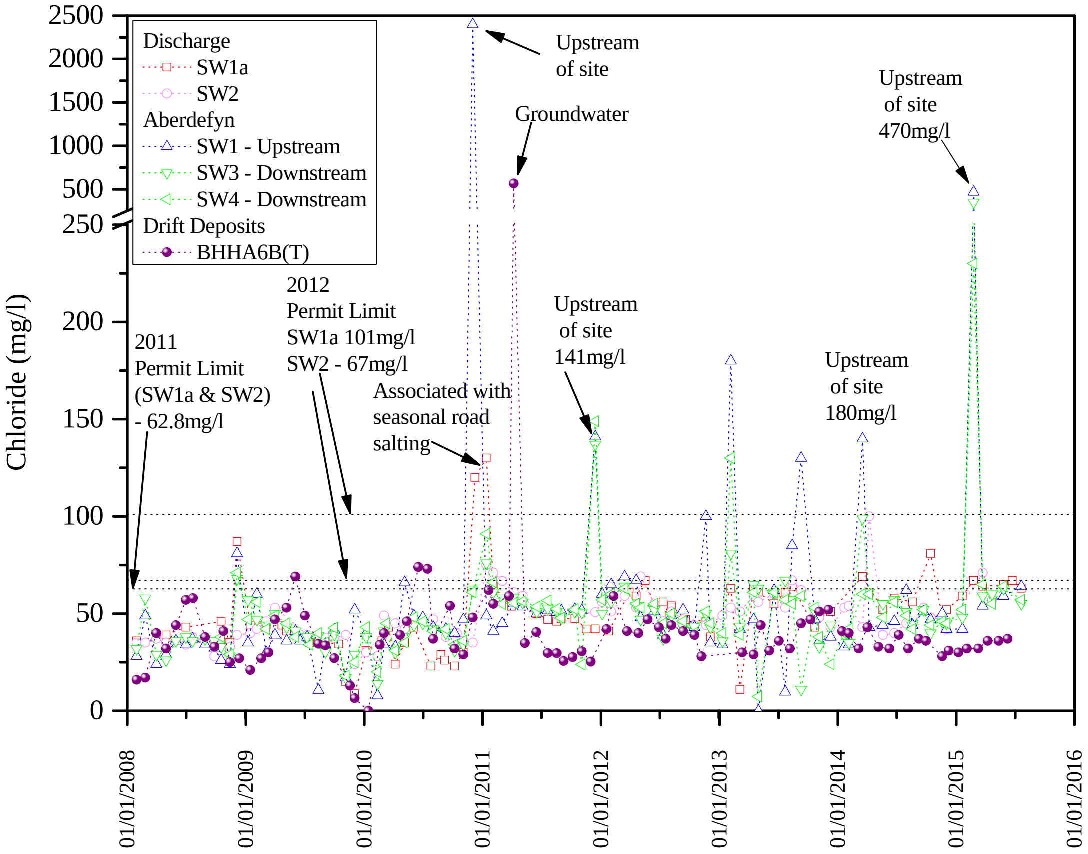


Figure 27 Surface Water Ammoniacal-N

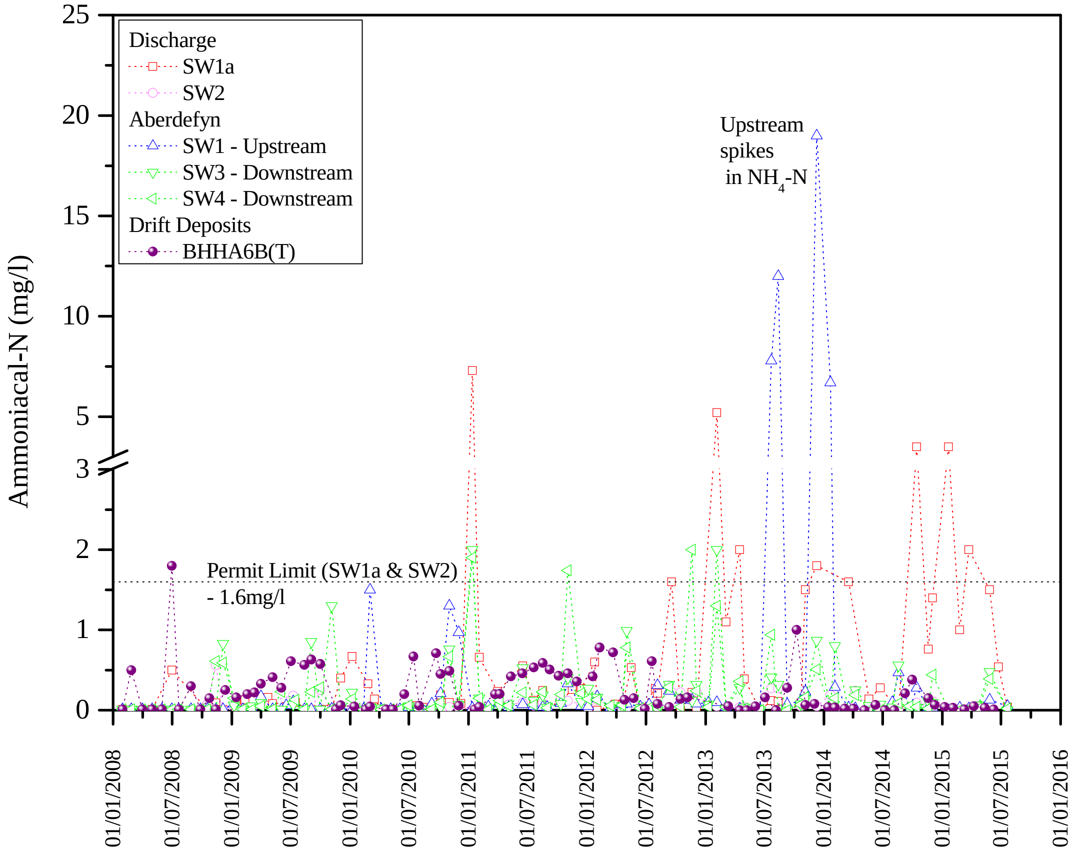


Table 13 Proposed Surface Water Monitoring Schedule

Determinand	Frequency	Site Discharge		Aberderfyn
		SW1a	SW2	SW1, SW3,
		Limit	Limit	Limit
		mg/l	mg/l	mg/l
NH_4-N	Monthly	1.8	1.8	None set
Cl		101	67	
Sus. Solids	Quarterly	50	50	
BOD		14	14	
Fe		0.17	0.17	

Table 14 Substances Proposed to be Removed from Surface Water Monitoring Schedule

Determinand	Frequency	Site Discharge		Aberderfyn
		SW1a	SW2	SW1, SW3,
		Limit	Limit	Limit
		mg/l	mg/l	mg/l
K	Monthly	15	10	None set
EC		1090	1120	
TON	Quarterly	2.9	2.9	
COD		67.9	67.9	
TOC		6.9	4.8	
Ca		185	185	
Mg		31.9	31.9	
Na		94.8	56.8	
SO_4		224.3	224.3	
Alkalinity		323	323	
Mn		0.86	0.86	
Cd		0.01	0.01	
Hg		None set	None set	
Cr		0.02	0.02	
Cu		0.13	0.13	
Ni		0.02	0.02	
Zn		0.064	0.064	
Pb		0.06	0.06	
DO		None set	None set	

9. CONCLUSIONS

The Hafod Landfill Site is a fully contained engineered landfill site with active emissions management, compliant with the Landfill and Groundwater Directives when originally permitted. The site is located within a natural geological barrier along the entire base and the majority of the sidewall of the site. Where the natural geological barrier does not extend to the full height of the sidewall, an artificial geological barrier with the provision of groundwater management has been established. There is not a discernible impact on groundwater quality from the site and at the present time, leachate is contained within the geological barrier and is topographically below the base of the nearest potential aquifer body.

Consequently Hafod landfill site complies with the requirements of the Landfill Directive and the Groundwater Daughter Directive of the Water Framework Directive.

Recommendations have been made to revise the Permit Limits for leachate level within the site. It is proposed that monitoring points outside of the zone of influence required by LFTGN02 are removed (*i.e.* locations on the A483 junction >260m distance from the site (*i.e.* BH HA12, which appear to be either acting as a conduit for road salt, or have intercepted an evaporite horizon within the ground) are replaced by new installations which are within the sphere of influence of the site. Proposals for the monitoring point relocation have been agreed with the NRW and a new monitoring point was installed in November 2015. A revised schedule, including a discussion regarding the suitability of the off-site locations, will be proposed when a period of comparative monitoring has been undertaken.

Recommendations have also been made to reduce the surface water monitoring schedule, to ensure that only locations within the site's influence are monitored (*i.e.* the removal of SW4) and that the monitoring schedule is simplified to target the identification of a leachate influence on surface water.

Appendix A

Water Quality Time Series Plots

Figure A1.1 Cell 1 Leachate Matrix Chemistry

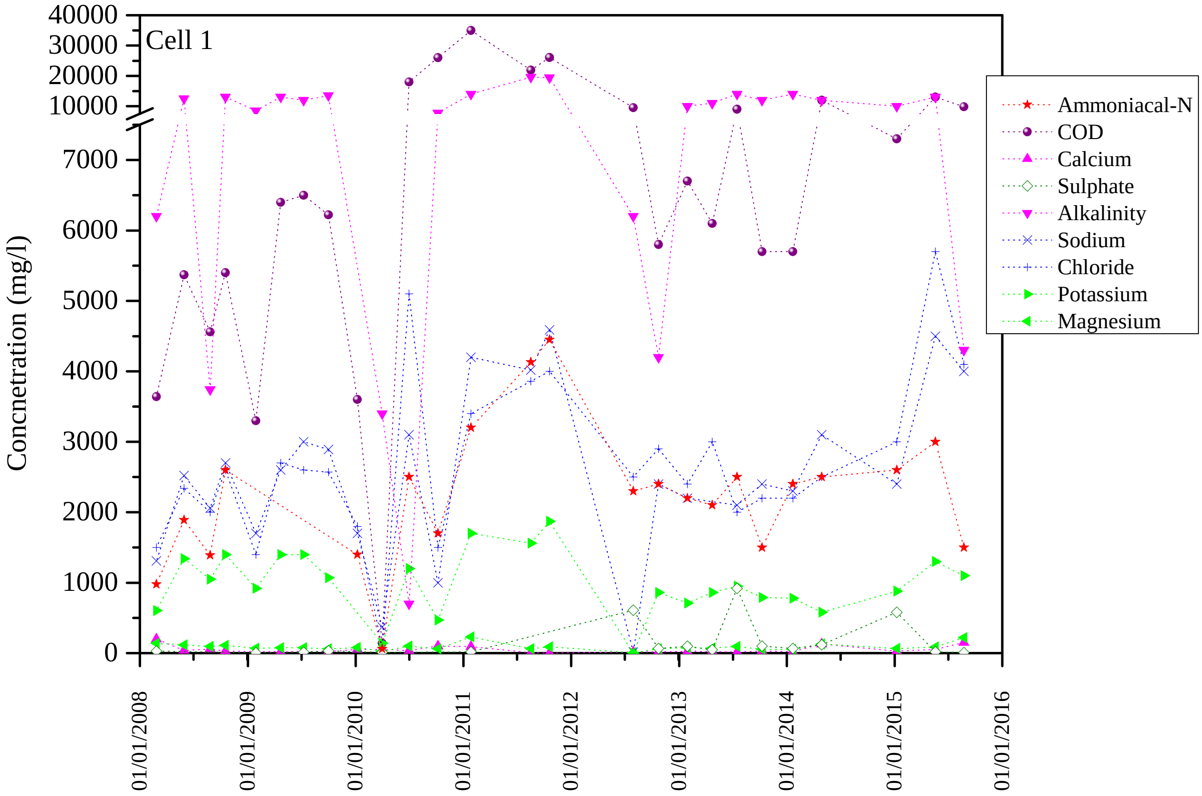


Figure A1.2 Cell 2 Leachate Matrix Chemistry

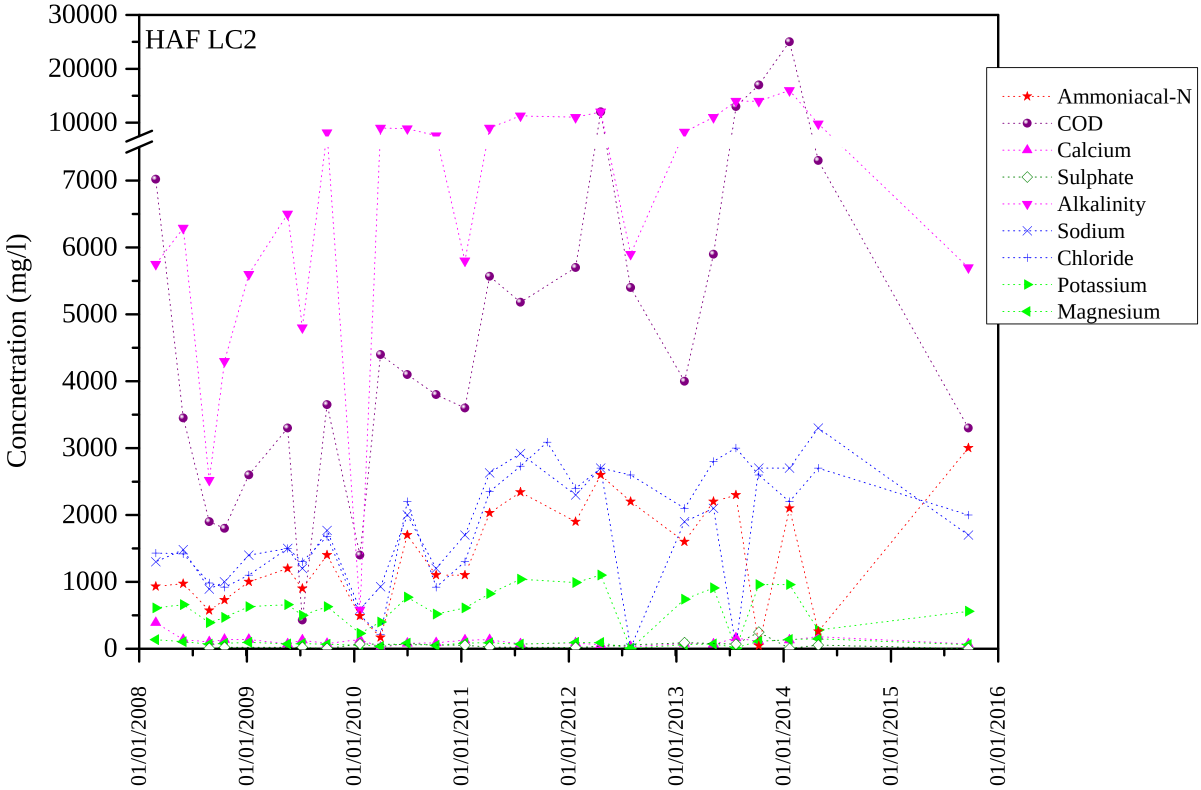


Figure A1.3 Cell 3 Leachate Matrix Chemistry

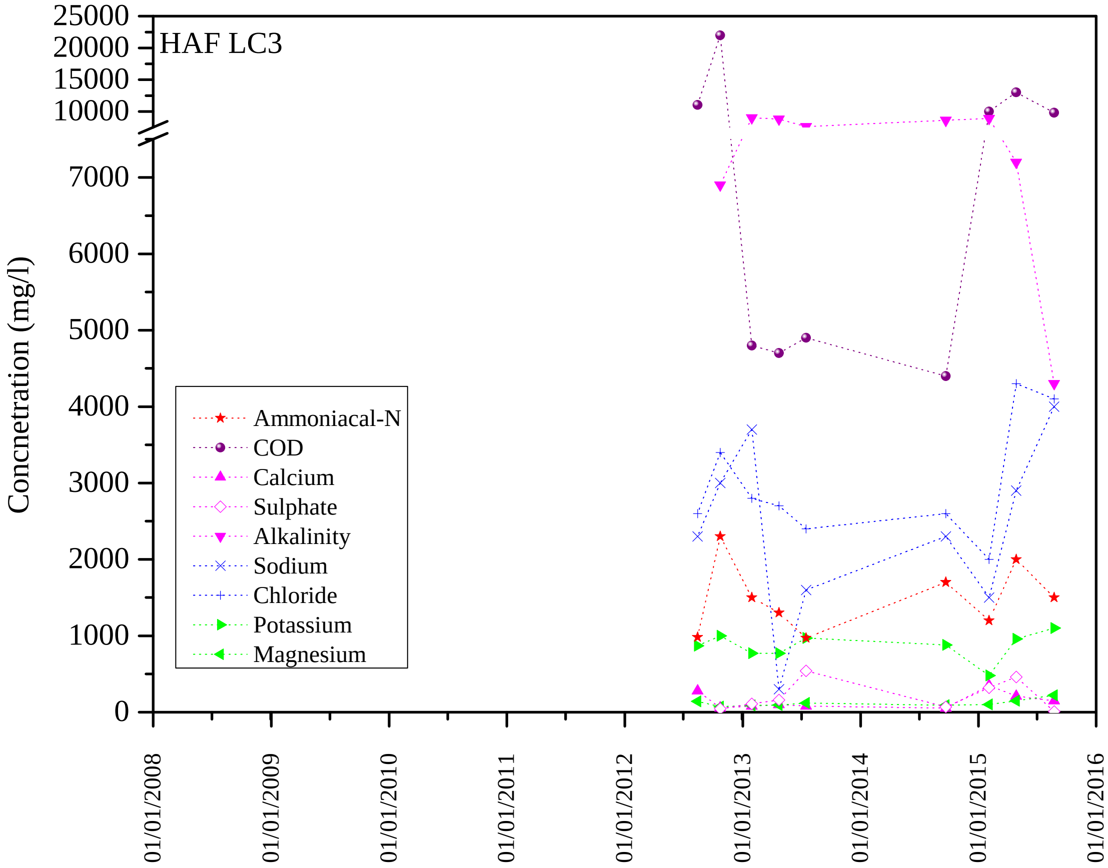


Figure A1.4 Leachate Ammoniacal-N

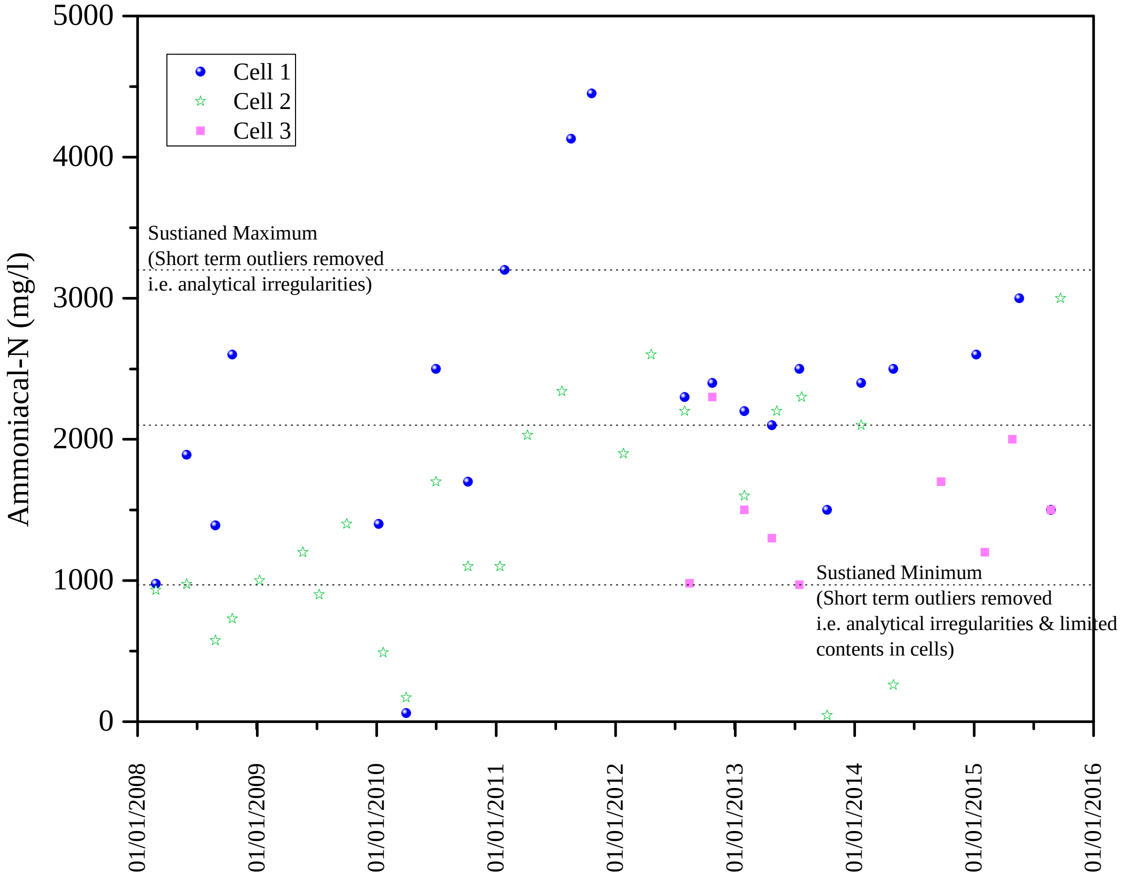


Figure A1.5 Leachate Chloride

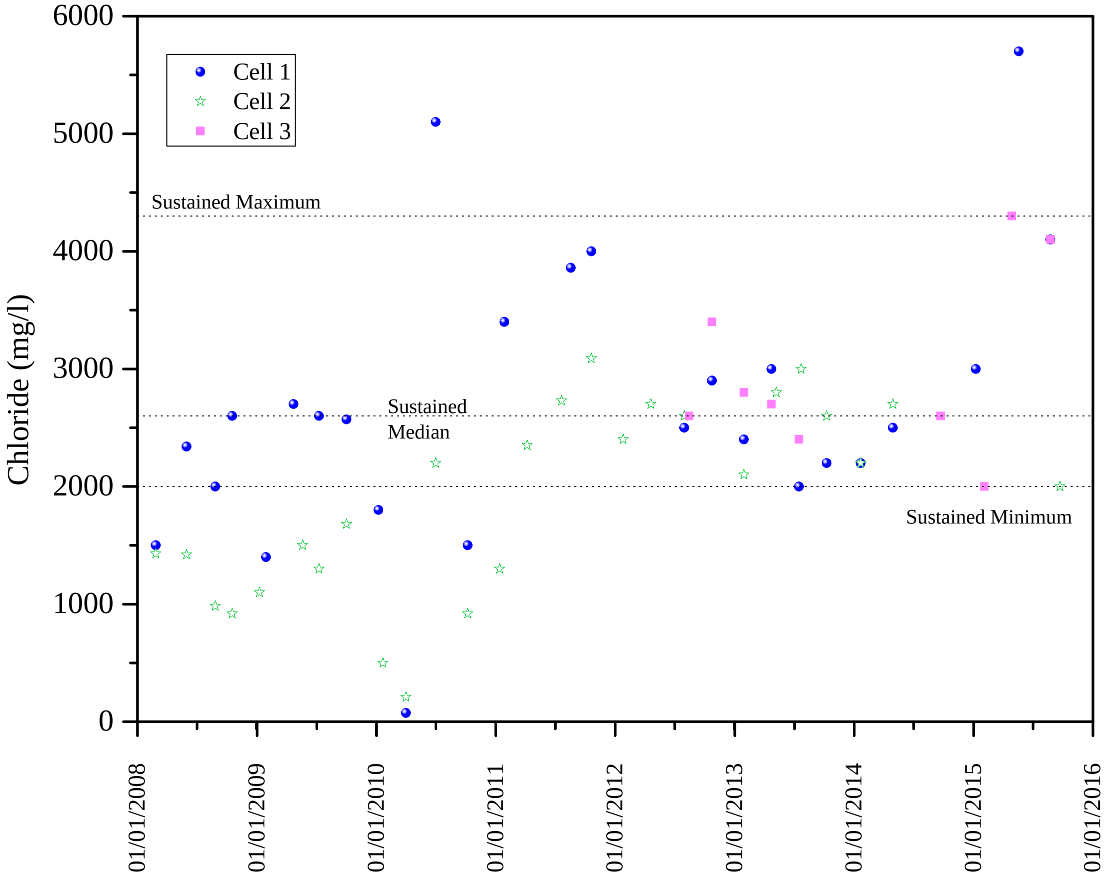


Figure A1.6 Leachate Non-hazardous Metals

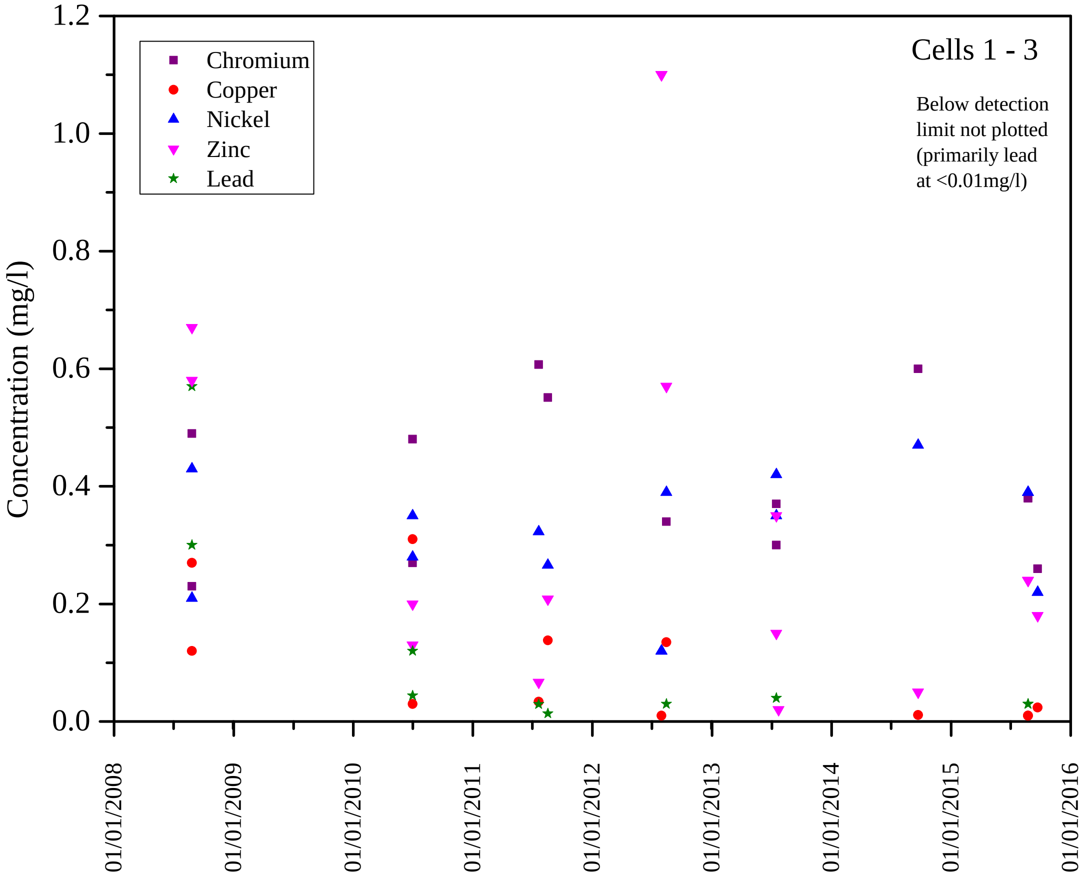


Figure A2.1 Groundwater BH HA01B(B) Matrix Chemistry

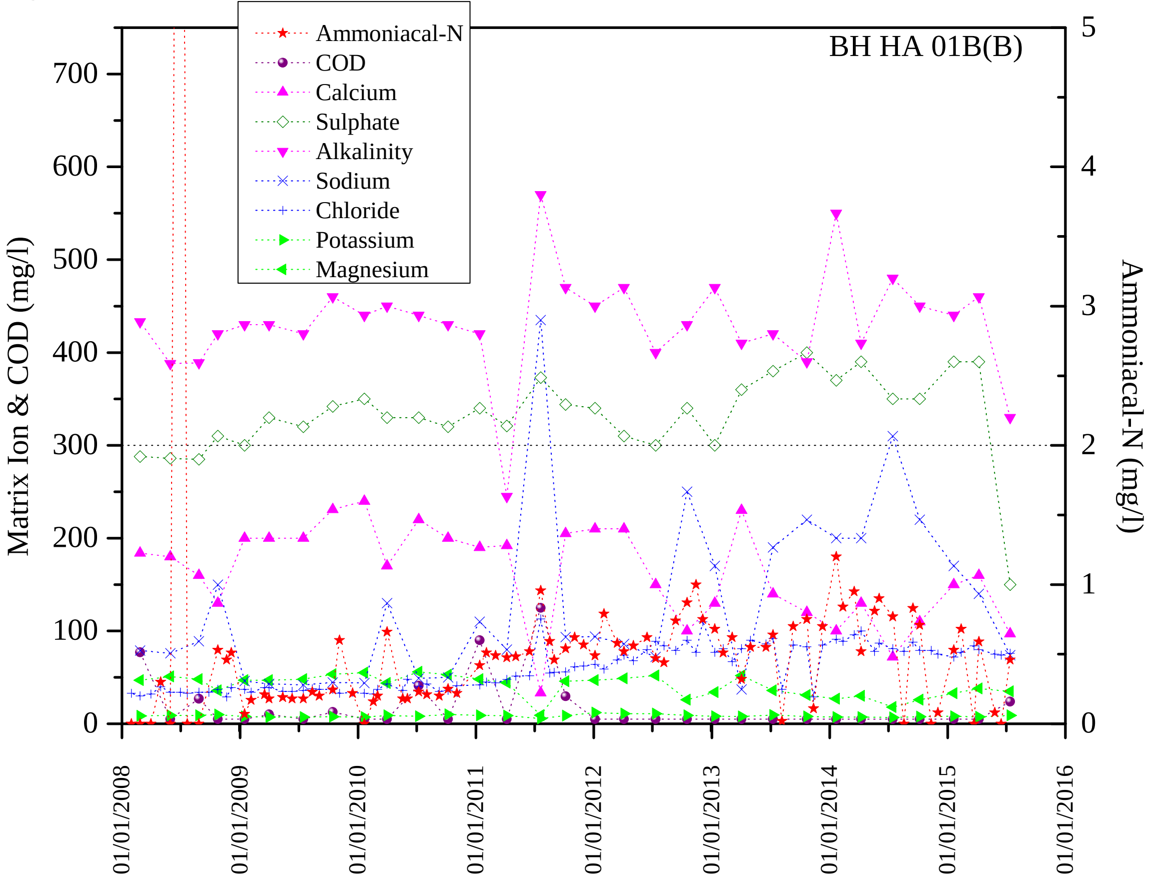


Figure A2.2 Groundwater Matrix Chemistry BHHA01B(M)

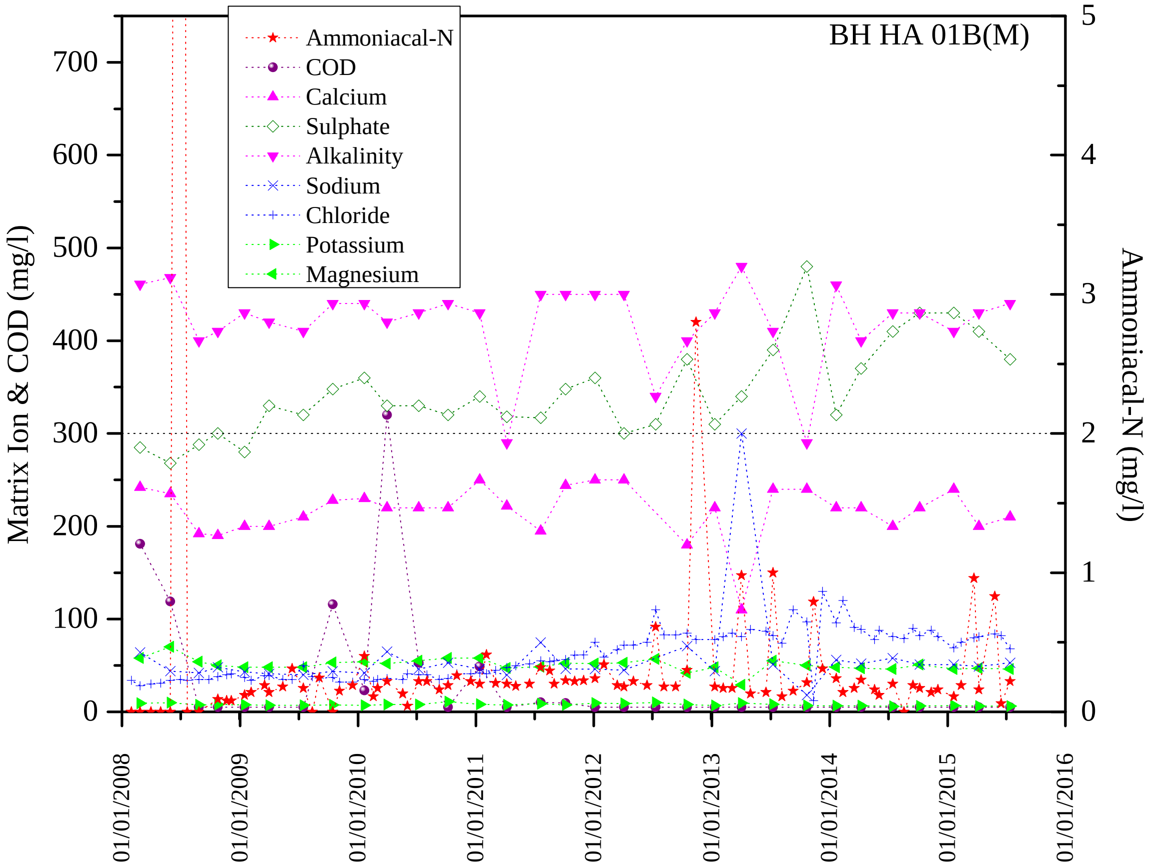


Figure A2.3 Groundwater Matrix Chemistry BHHA02A(T)

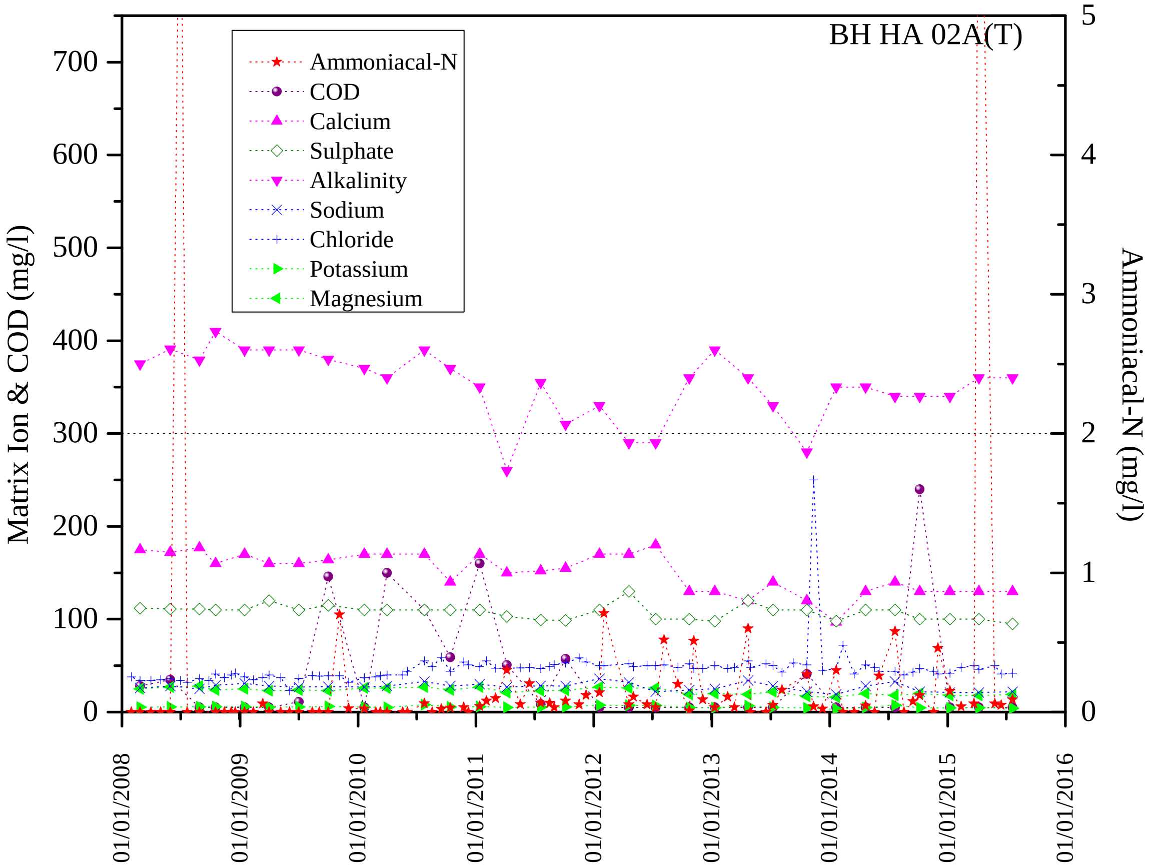


Figure A2.4 Groundwater Matrix Chemistry BHHA02A(M)(

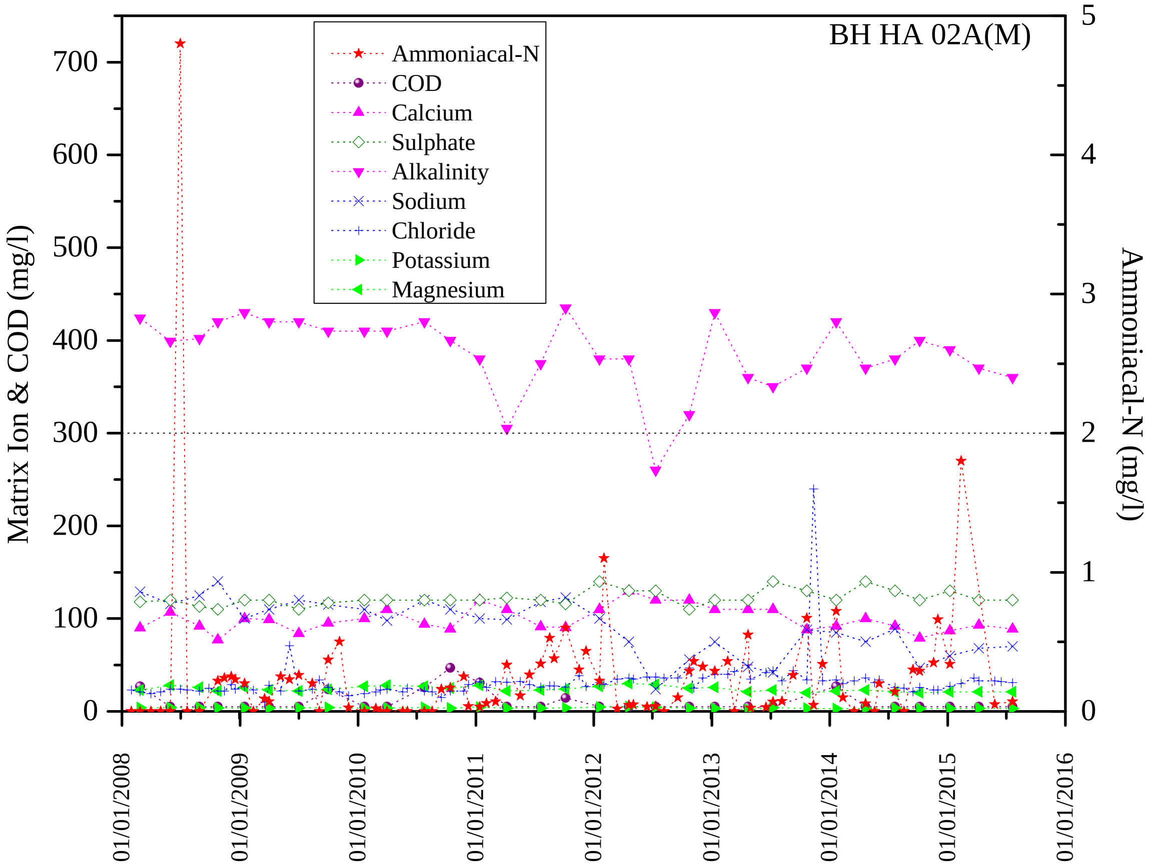


Figure A2.5 Groundwater Matrix Chemistry BHHA02B(B)

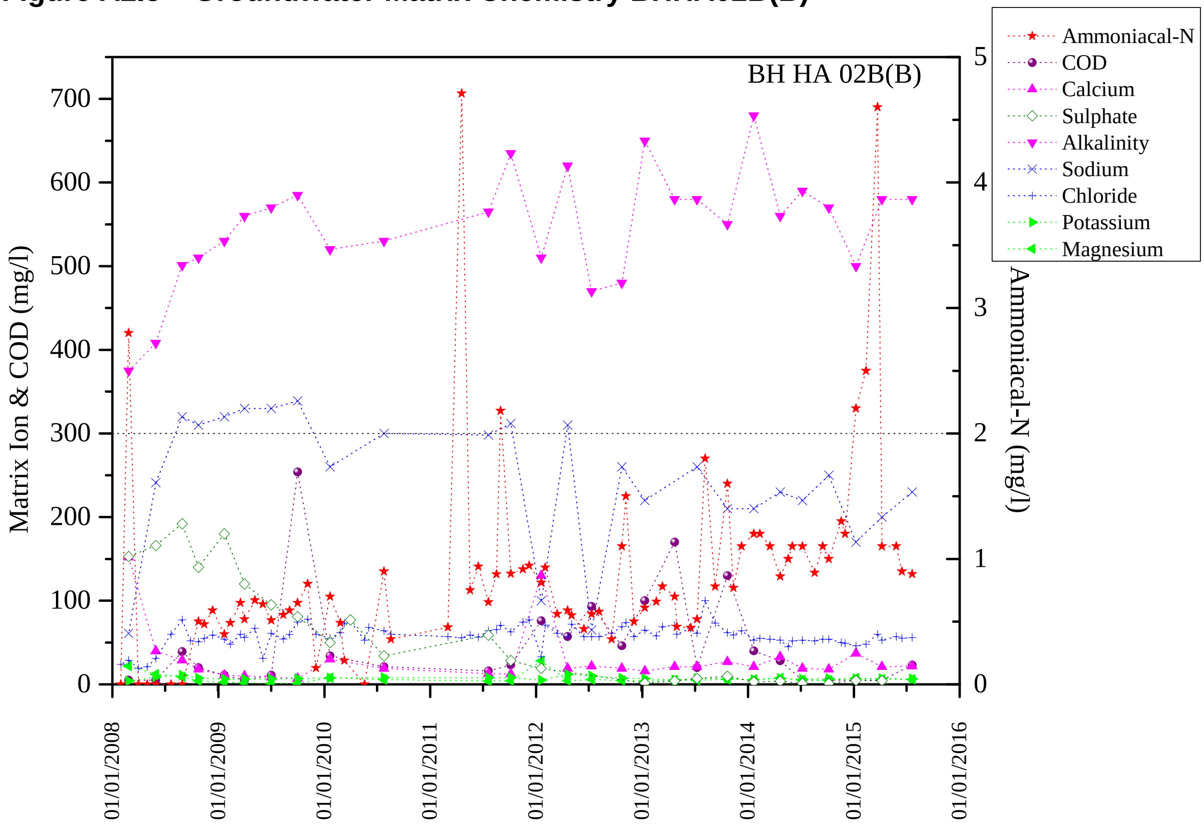


Figure A2.6 Groundwater Matrix Chemistry BHHA04(B)

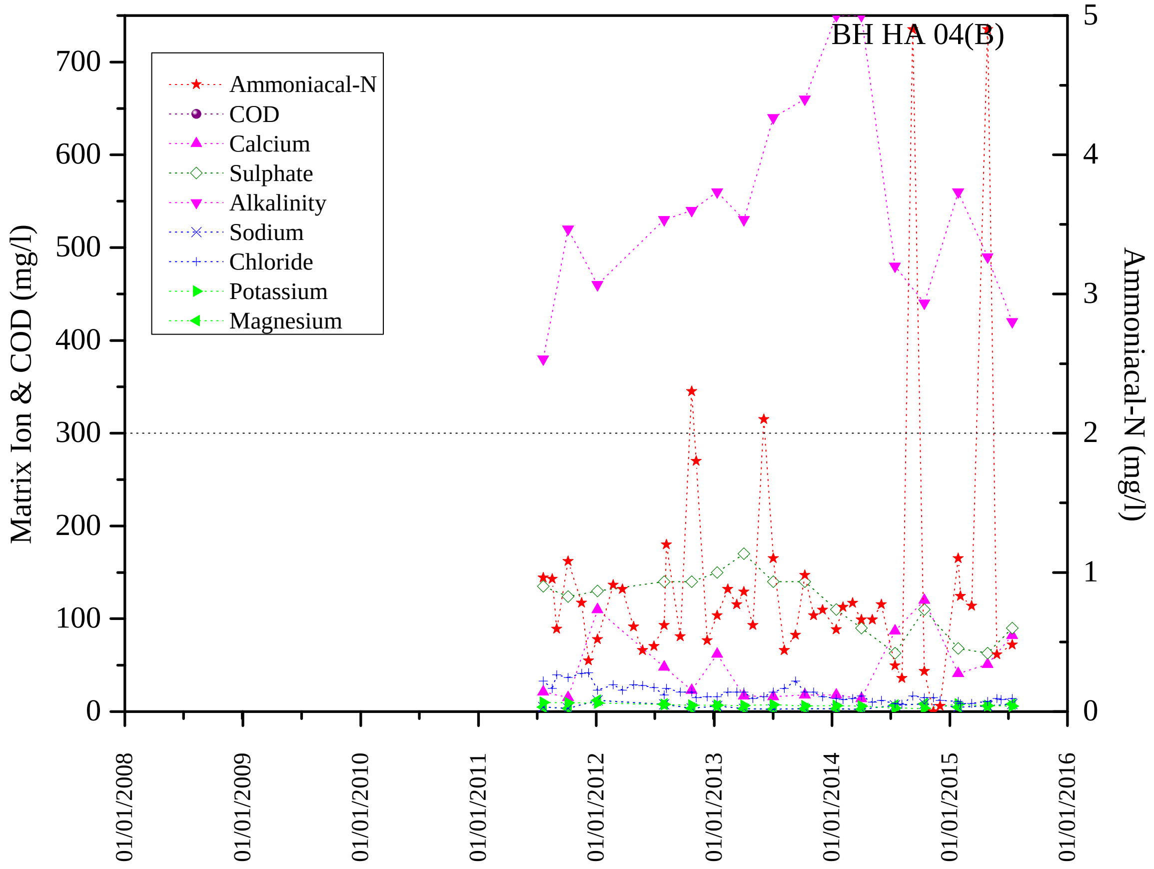


Figure A2.7 Groundwater Matrix Chemistry BHHA05(B)

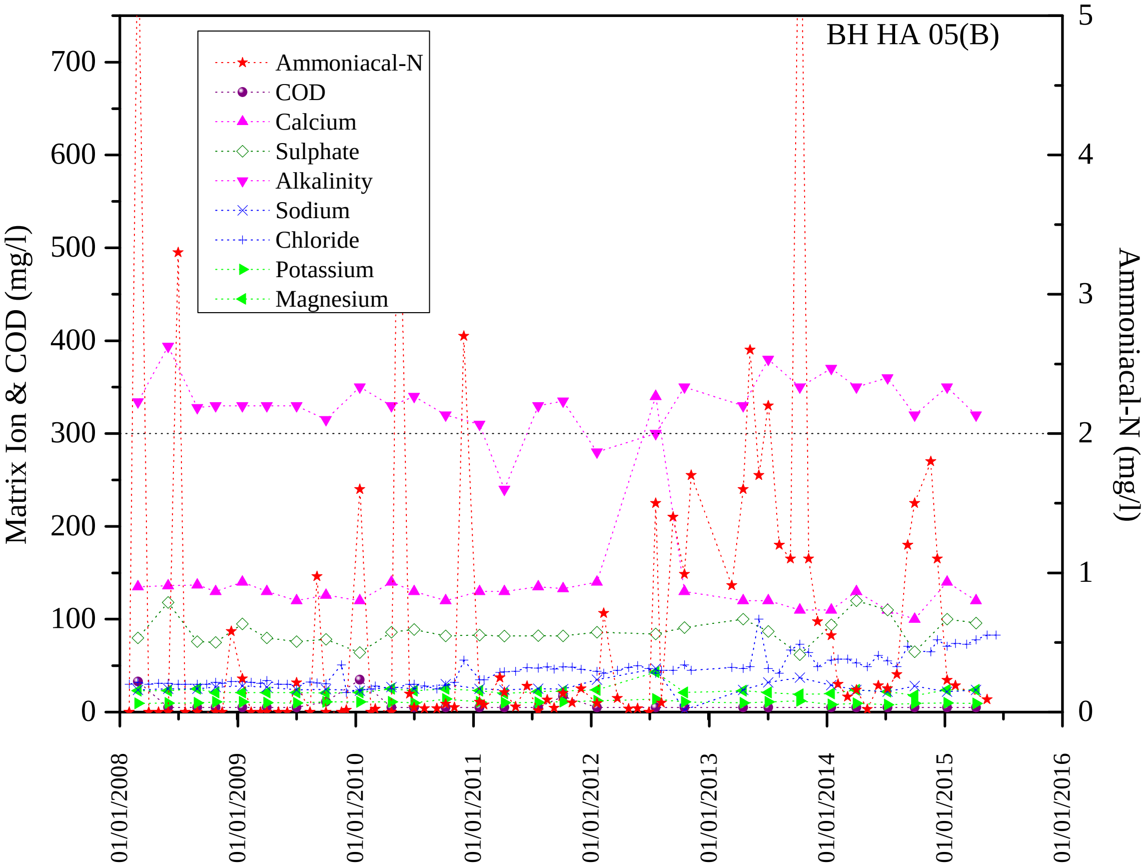


Figure A2.8 Groundwater Matrix Chemistry BHHA06B(T)

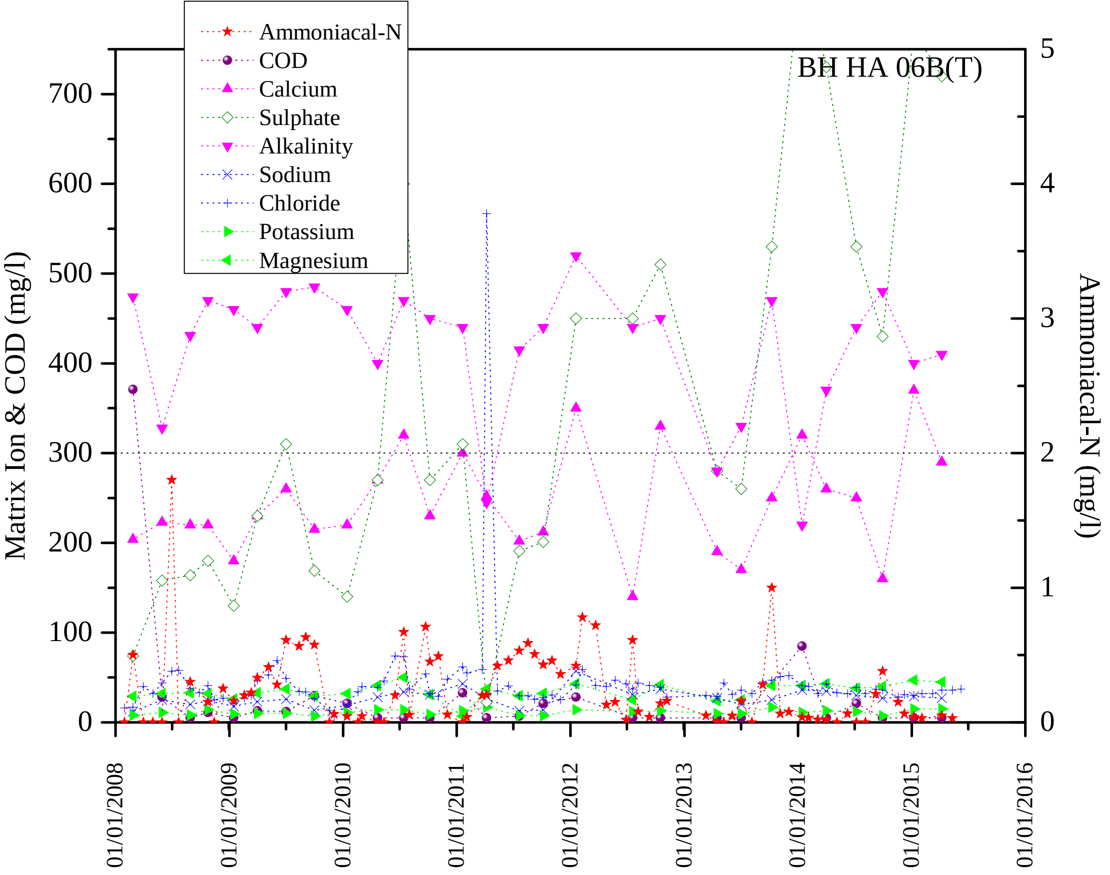


Figure A2.9 Groundwater Matrix Chemistry BHHA06A(M)

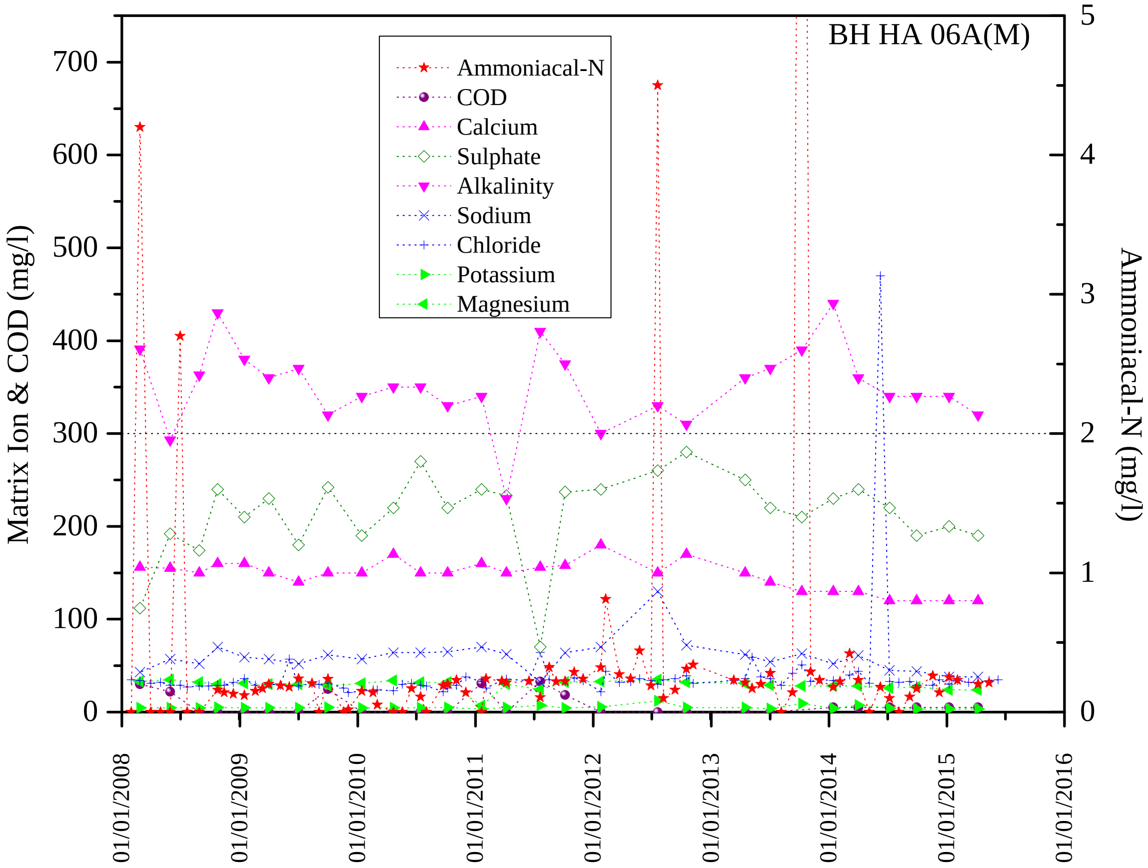


Figure A2.10 Groundwater Matrix Chemistry BHHA06A(B)

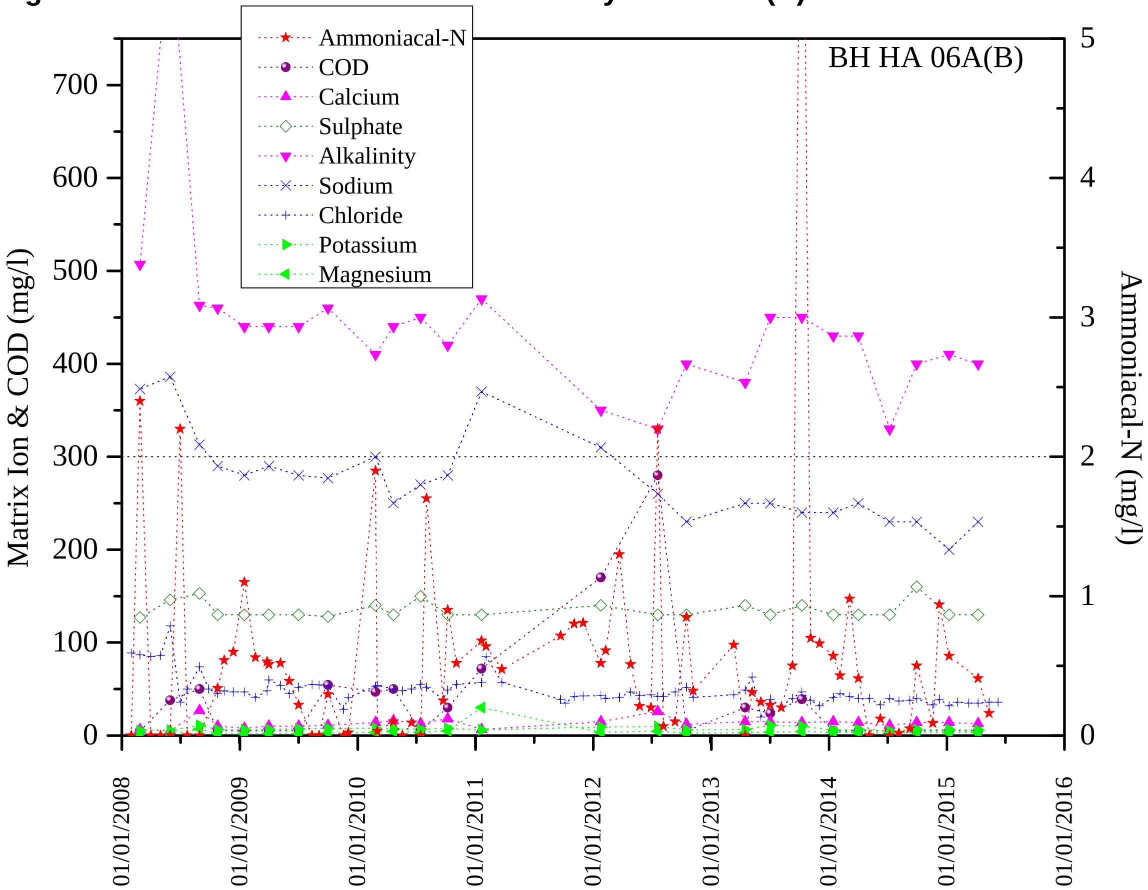


Figure A2.11 Groundwater Matrix Chemistry BHHA09B(M)

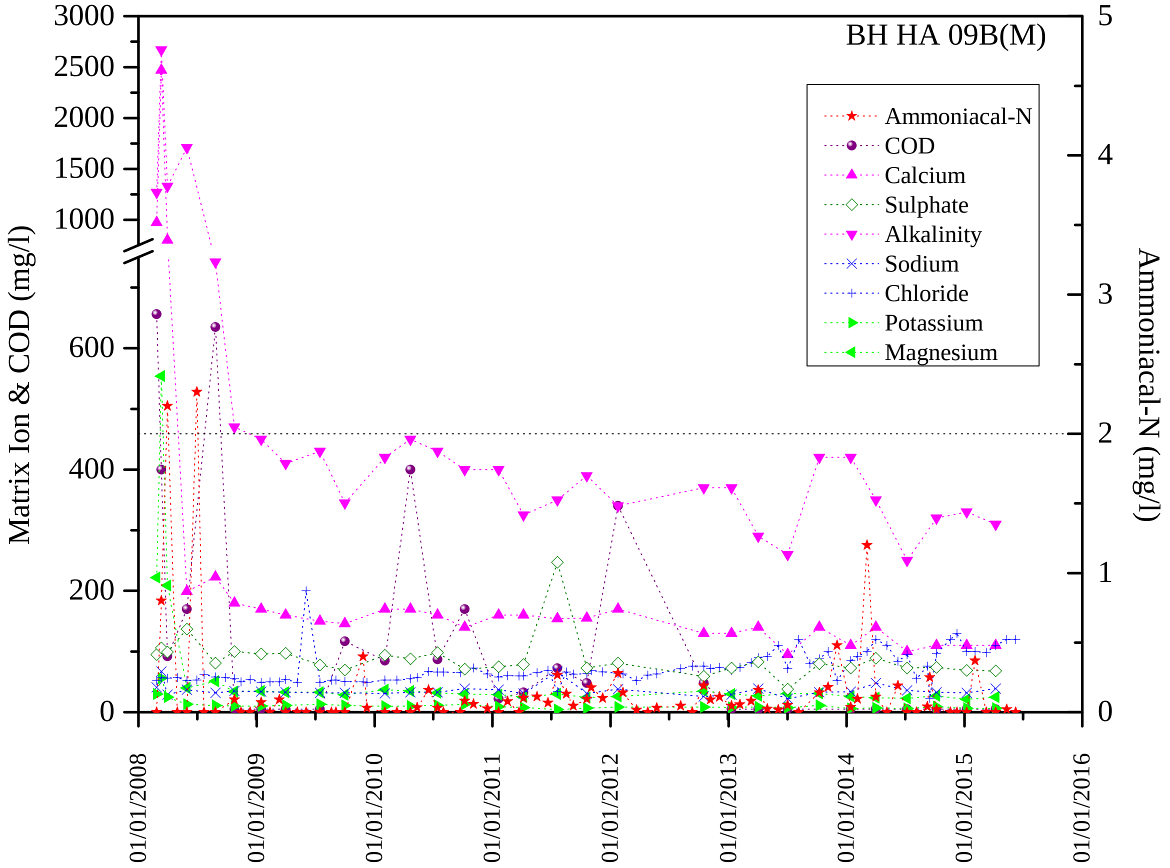


Figure A2.12 Groundwater Matrix Chemistry BHHA09A(B)

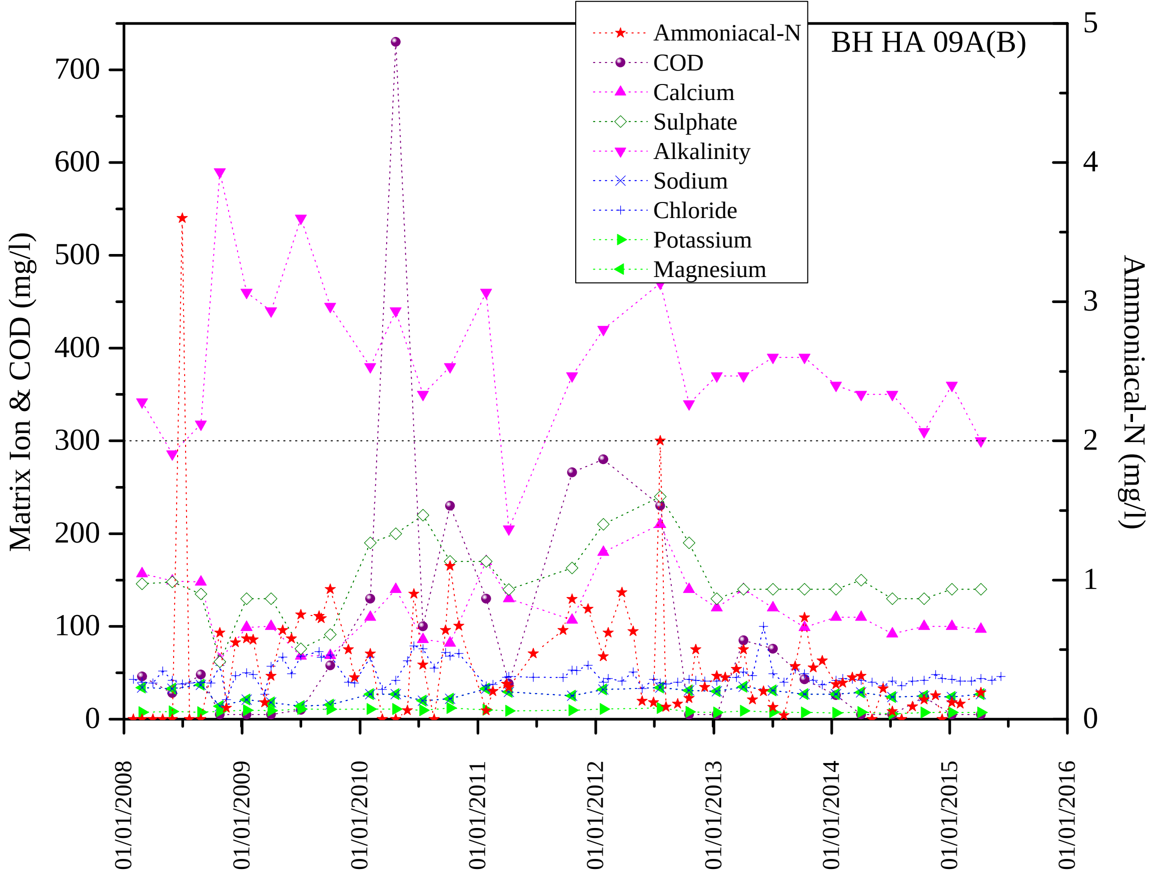


Figure A2.13 Groundwater Matrix Chemistry BHHA10(T)

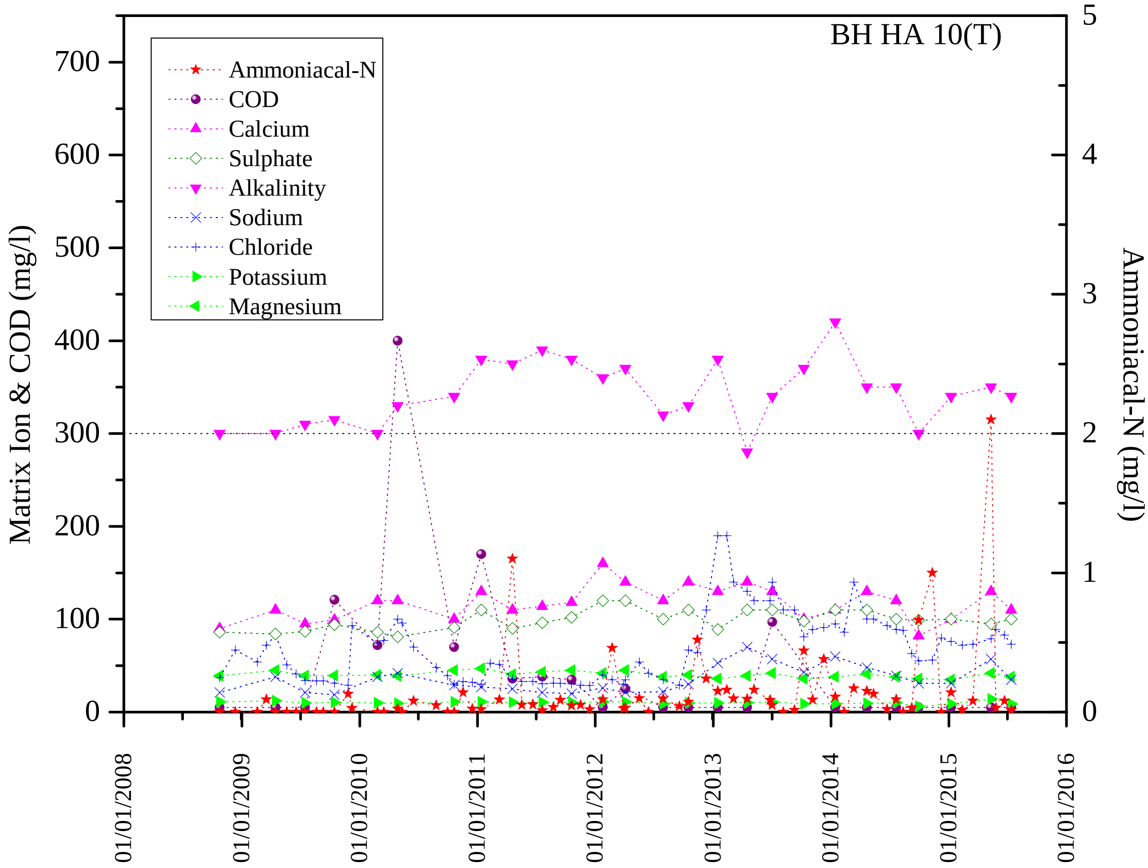


Figure A2.14 Groundwater Matrix Chemistry BHHA10(B)

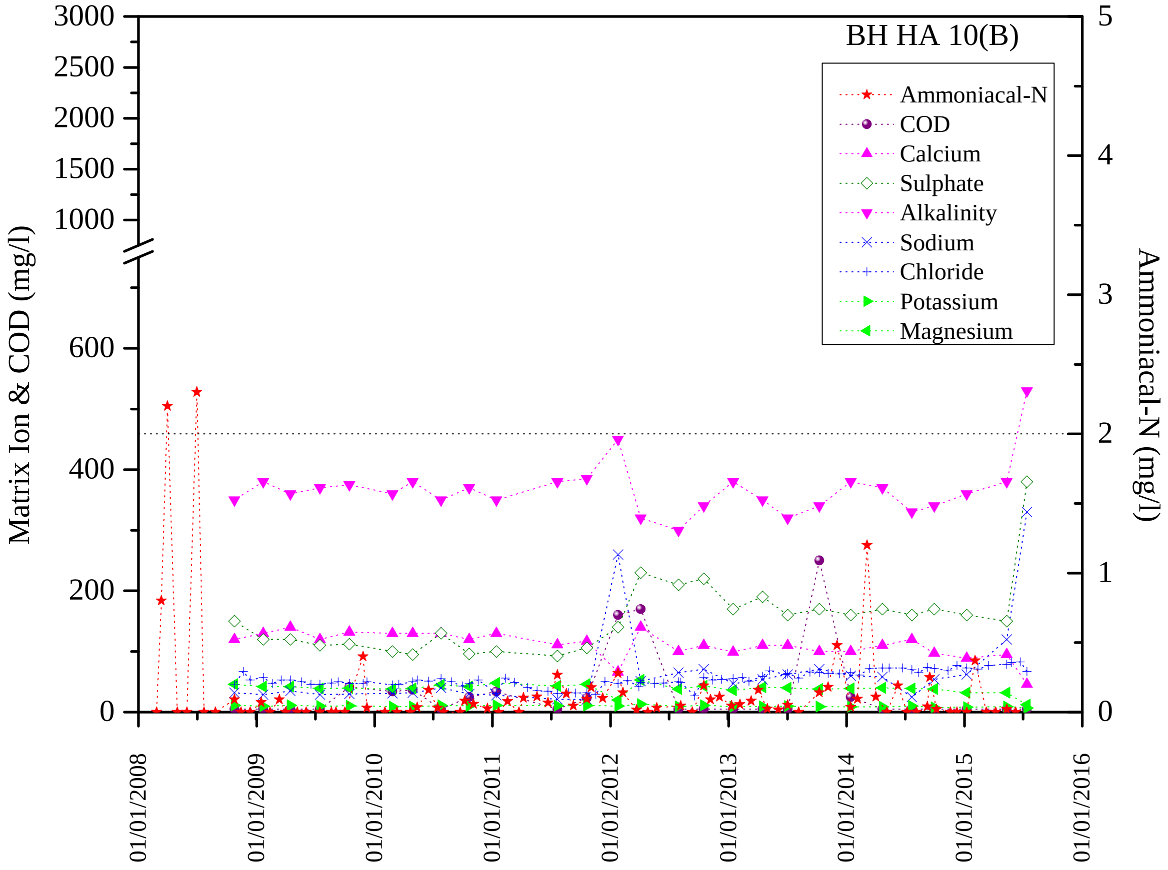


Figure A2.15 Groundwater Matrix Chemistry BHHA11B(T)

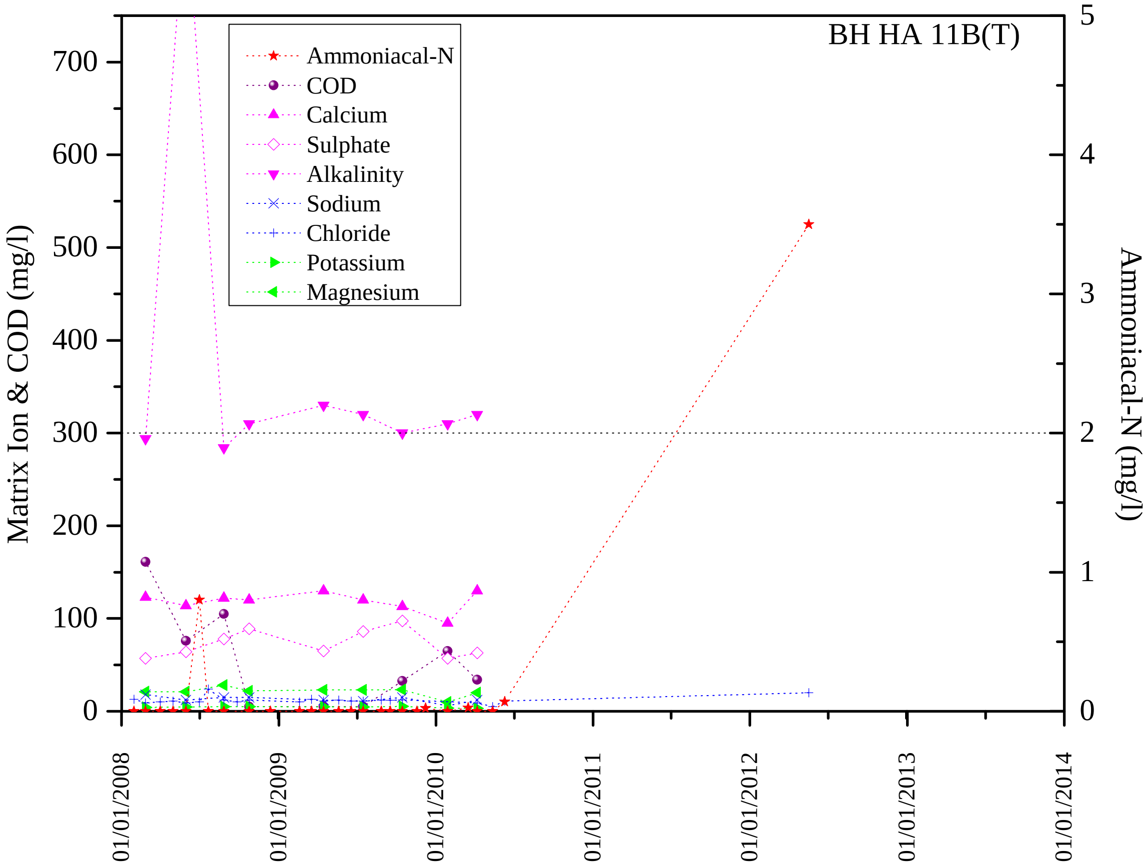


Figure A2.16 Groundwater Matrix Chemistry BHHA11B(M)

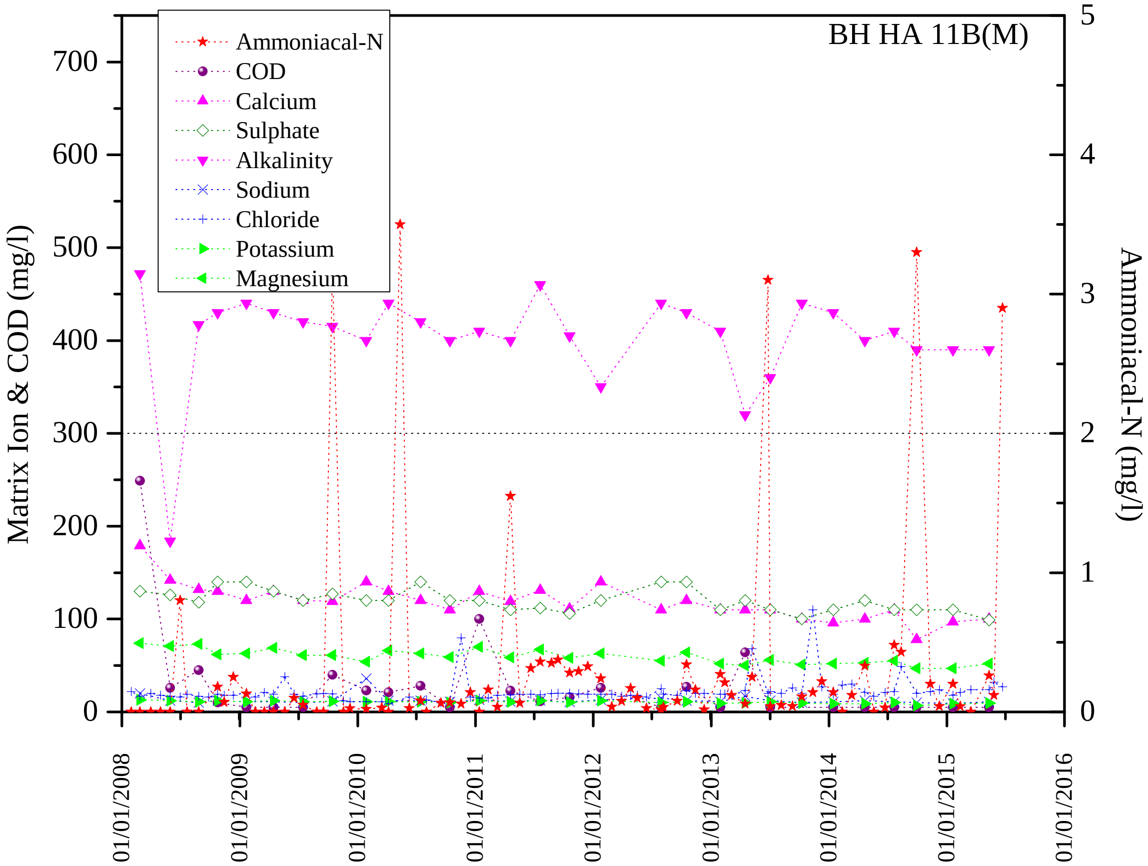


Figure A2.17 Groundwater Matrix Chemistry BHHA11A(B)

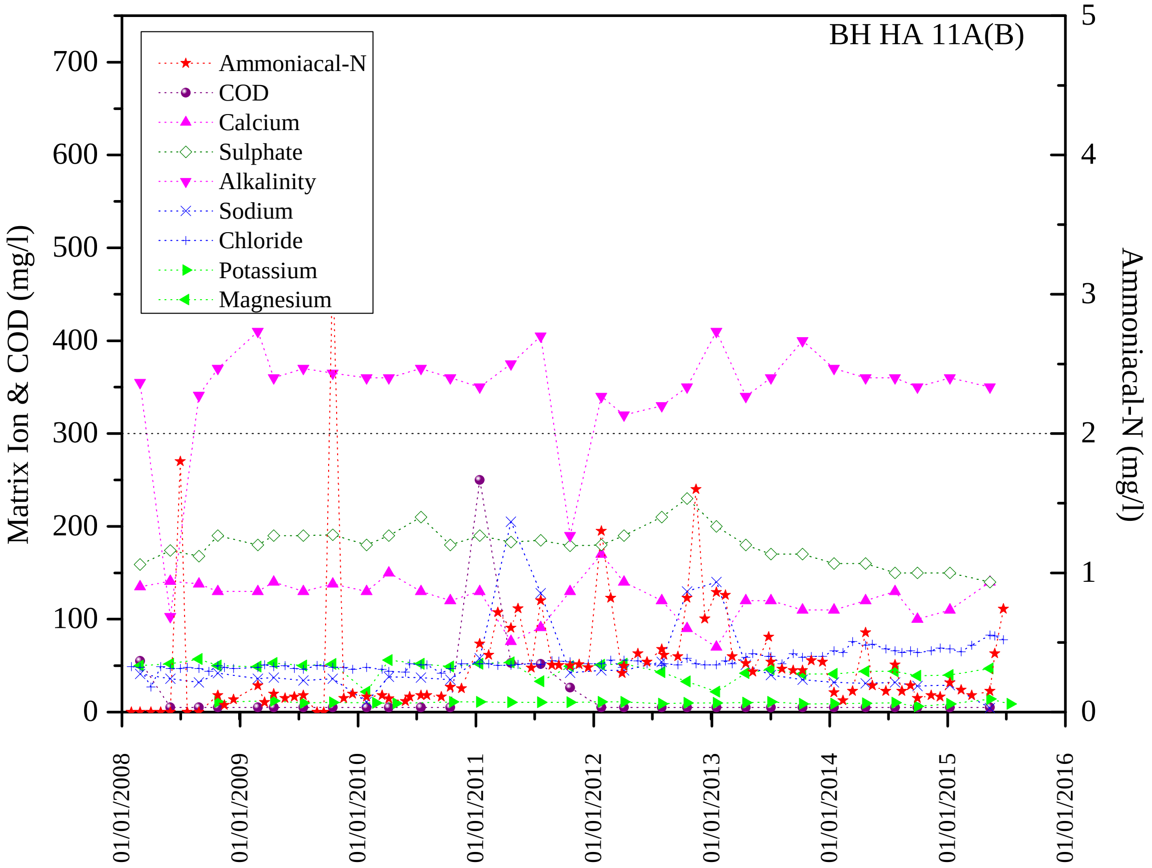


Figure A2.18 Groundwater Matrix Chemistry BHHA12A(M)

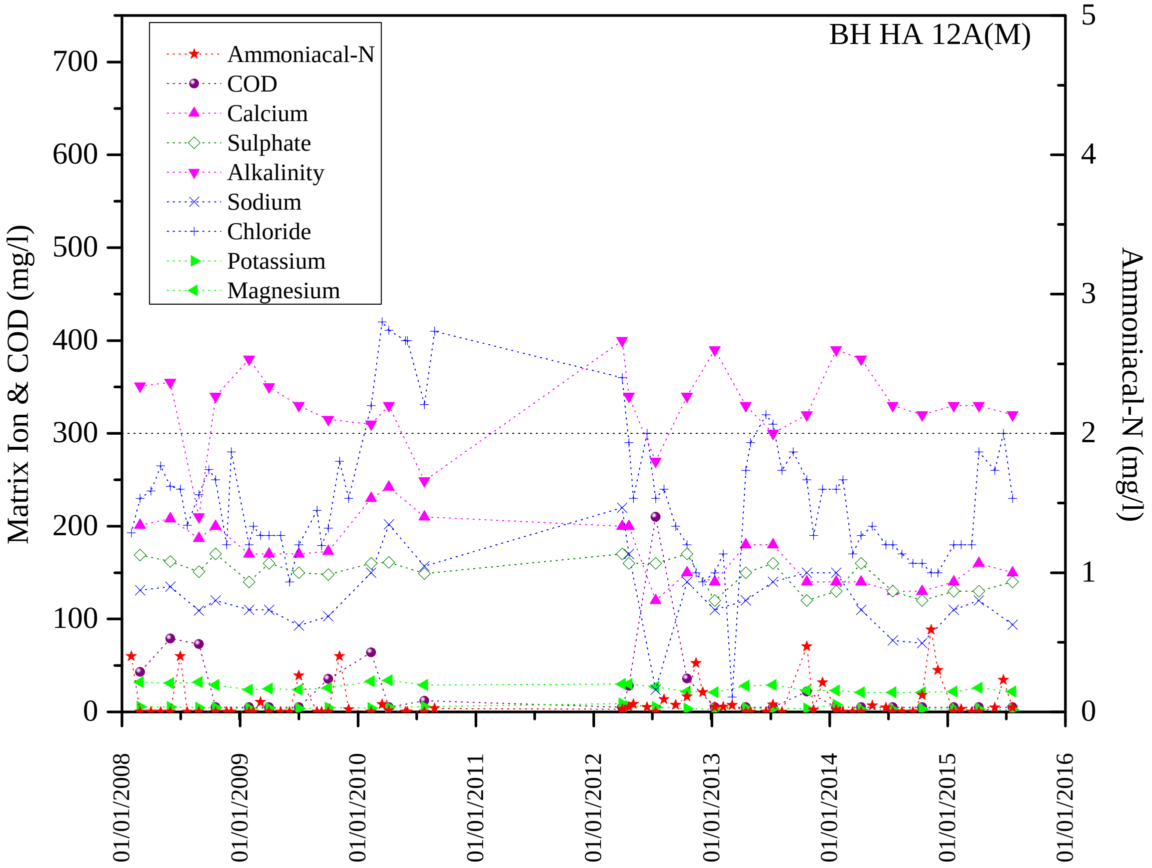
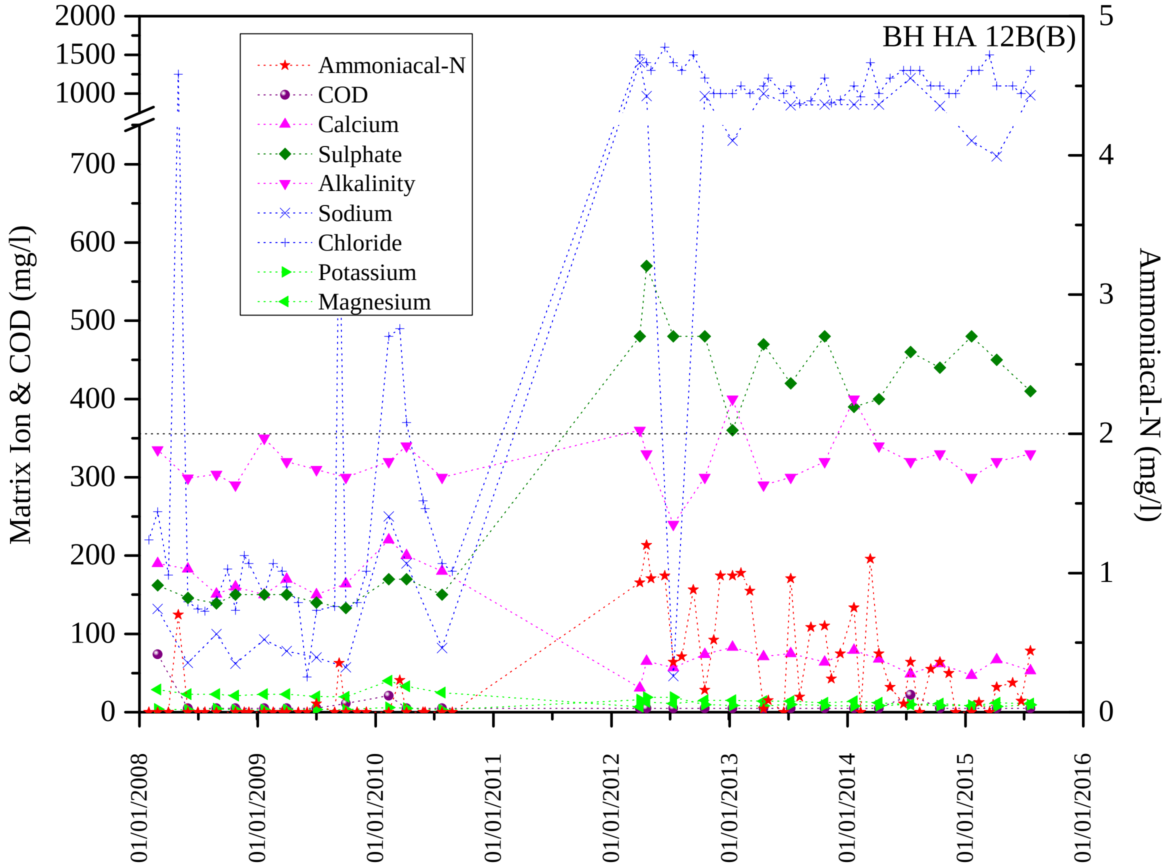


Figure A2.19 Groundwater Matrix Chemistry BHHA12B(B)



Appendix B

Model Files

Hafod Landfill Site 5 October 2015

CONCEPTUAL MODEL AND LANDFILL CONSTRUCTION

Conceptual model of landfill construction	CM	3	-
Is a geomembrane present?	GM_opt	No	-
Basal width perpendicular to groundwater flow	Width_LF	250	m
Basal length parallel to groundwater flow	Length_LF	100	m
Basal area	Base_Area	25000	m2
Elevation of base of landfill	LFbase_elev	72	maOD
Elevation of base of aquifer	Aqbound_elev	84	maOD
Leachate head inside landfill	Head_inLF	90	maOD
Groundwater head outside landfill	Head_outLF	91	maOD
Area of liner below the water table	Area_contact	4200	m2

CONTAMINANT PARAMETERS

Contaminant name	Cont_Nme	Ammoniacal-N	-
Contaminant type	Cont_Type	Inorganic	-
Contaminant classification	Cont_Class	List II	-
Concentration in landfill leachate	Conc_LF	3200	mg/l
Free water diffusion coefficient	Dw_cl	1.96E-09	m2/s
Partition coefficient in clay	Kd_cl	1.25	l/kg
Retardation factor in clay	R_cl	22.42857143	-
Half life in clay (0 for no decay)	thalf_cl	0	days
Decay in sorbed phase?	Decay_sorb	No	-
Decay constant in clay	Decay_cl	0	1/s

MINERAL BARRIER / LINER

Thickness of mineral liner	thick_clbr	1.075	m
Hydraulic conductivity	k_cl	1.93E-10	m/s
Average pore radius	pore_radius	1.00E-05	m
Effective porosity	n	0.105	-
Dry bulk density	rho	1800	kg/m3
Tortuosity	tau_cl	10	-

Ammoniacal-N

STEADY STATE DILUTION

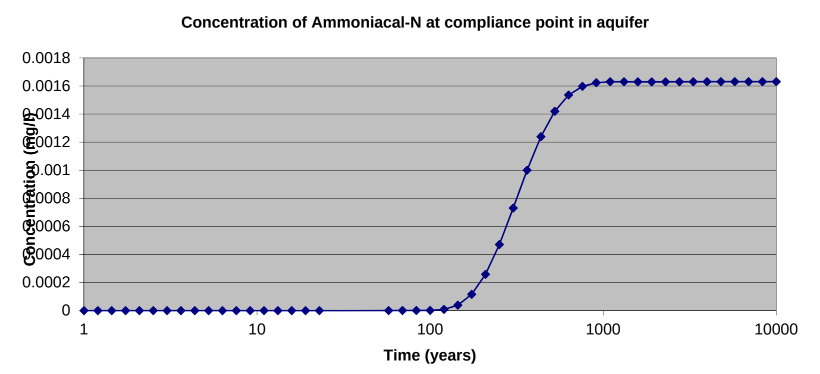
Hydraulic gradient in the aquifer	aq_I	0.0013	-
Hydraulic conductivity of the aquifer	k_aq	5.50E-05	m/s
Downgradient distance of compliance point from landfill	dist_cp	50	m
Mixing width	Mix_W	250	m
Mixing depth	Mix_D	7	m
Dilution flow in aquifer downstream to the landfill	aq_Q	0.000125125	m3/s

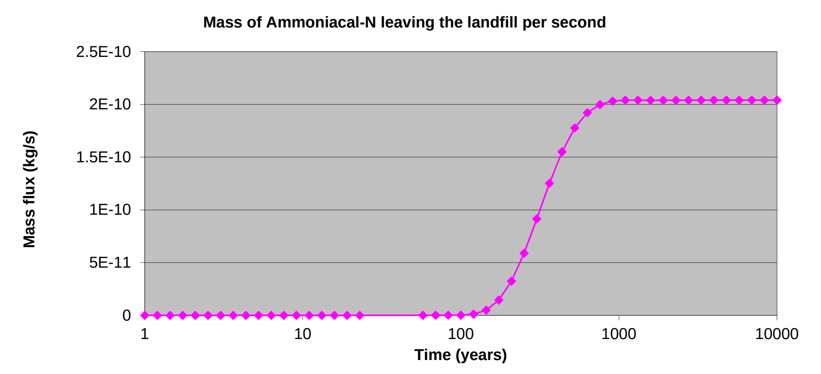
CONTAMINANT AND WATER FLUXES

Groundwater flux into landfill		1.50809E-06	m3/s
Maximum contaminant concentration at compliance point at tmax	C_comp	0.001630993	mg/l

CHART PARAMETERS

Minimum axis display	tmin	1	years
Maximum axis display	tmax	1.00E+04	years





Hafod Landfill Site **5 October 2015**
Craig Fannin

CONCEPTUAL MODEL AND LANDFILL CONSTRUCTION

				Justification / Reference / Notes
Scenario		3		as per 2010 HRA
Is a geomembrane present?		No		Clay barrier
Basal width perpendicular to groundwater flow	Width_LF	250	m	as per 2010 HRA
Basal length parallel to groundwater flow	Length_LF	100	m	as per 2010 HRA
Elevation of base of landfill	LFbase_elev	72	maOD	as per 2010 HRA
Elevation of base of aquifer	Aqbound_elev	84	maOD	reduced from 89mAOD to 84mAOID to increase flux
Leachate head inside landfill	Head_inLF	90	maOD	Foam Height
Groundwater head outside landfill	Head_outLF	91	maOD	BH9 limestone groundwater height

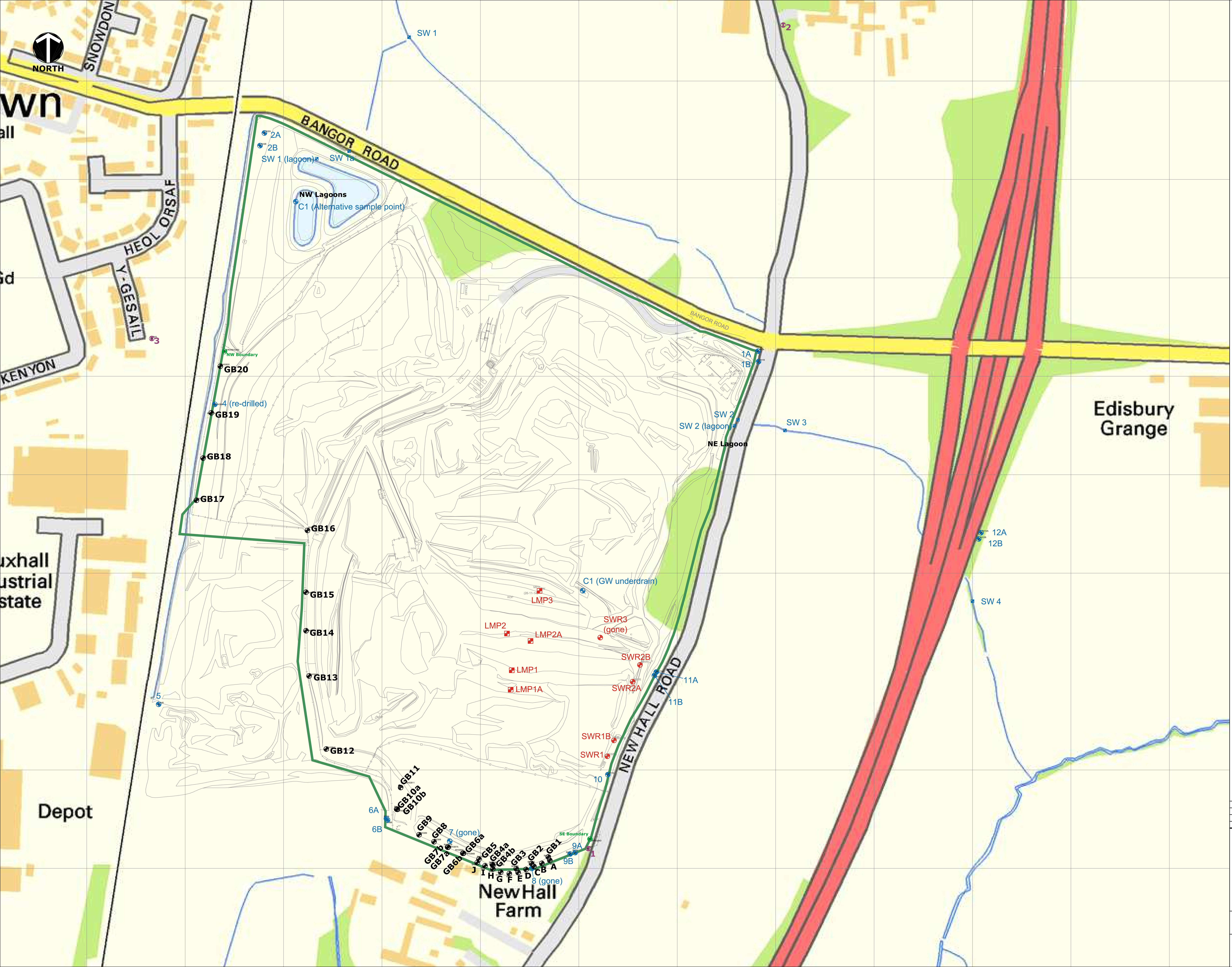
CONTAMINANT PARAMETERS

Contaminant name	Cont_Nme	Ammoniacal-N	-	MAximum leachate concentration
Contaminant type	Cont_Type	Inorganic	-	
Contaminant classification	Cont_Class	List II	-	
Concentration in landfill leachate	Conc_LF	3200	mg/l	
Free water diffusion coefficient	Dw_cl	1.96E-09	m2/s	
Partition coefficient in clay	Kd_cl	1.25	l/kg	
Half life in clay (0 for no decay)	thalf_cl	0	days	
Decay in sorbed phase?	Decay_sorb	No	-	

MINERAL BARRIER / LINER

Thickness of mineral liner	thick_clbr	1.075	m	minimum thickness likely to be constructed
Hydraulic conductivity	k_cl	1.93E-10	m/s	sensitivity analysis
Average pore radius	pore_radius	0.00001	m	
Effective porosity	n	0.105	-	
Dry bulk density	rho	1800	kg/m3	
Tortuosity	tau_cl	10	-	

Drawings



Key

🟥	Leachate extraction sump
●	Leachate monitoring well
■	Surface water monitoring point
●	Ground water monitoring borehole
●	Gas monitoring borehole
⊗	Dust monitoring point
⊗	Noise monitoring point

CORY ENVIRONMENTAL

Greyfriars Business Park
Frank Foley Way, Greyfriars
Stafford, ST16 2ST
Tel: (01785 251555)

Revision:	Details:

Site:

HAFOD

Title:

Environmental Monitoring Location Summary

Drawn:	Date:	Scale @ A2:
TJG	5-3-15	1:2500

Drawing number & cad reference

HAF092

Proposed GW Borehole location
Est Ground level 102.7m AOD

Key

● Proposed GW Borehole

CORY environmental

Units 3-6 Greyfriars Business Park,
Frank Foley Way, Stafford, ST16 2ST
Tel: 01785 251555

Revision:	Details:

Site:

HAFOD

Title:

Proposed Location of Groundwater Borehole

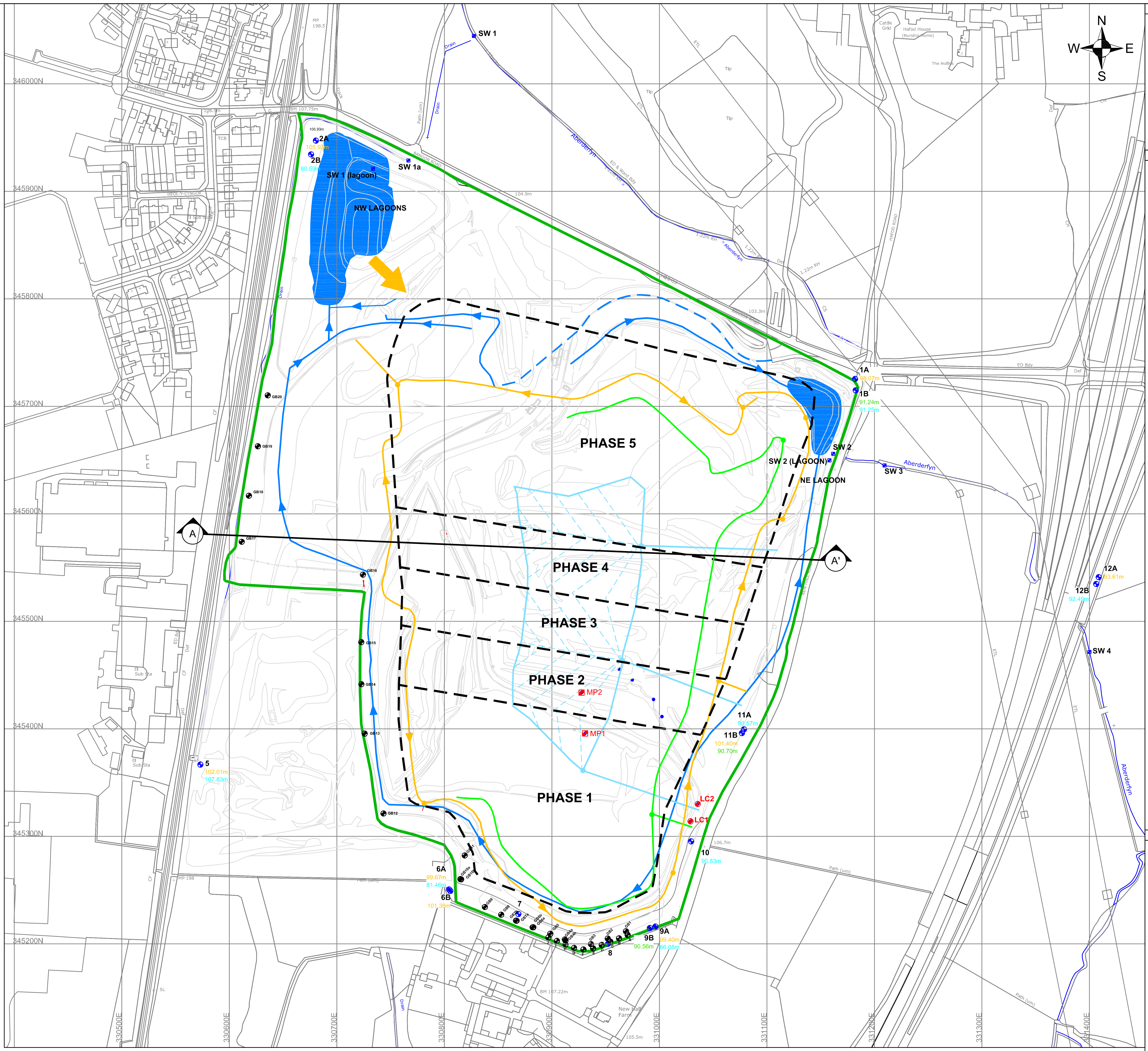
Drawn:	Date:	Scale @A3:
TJG	6-10-15	1:500

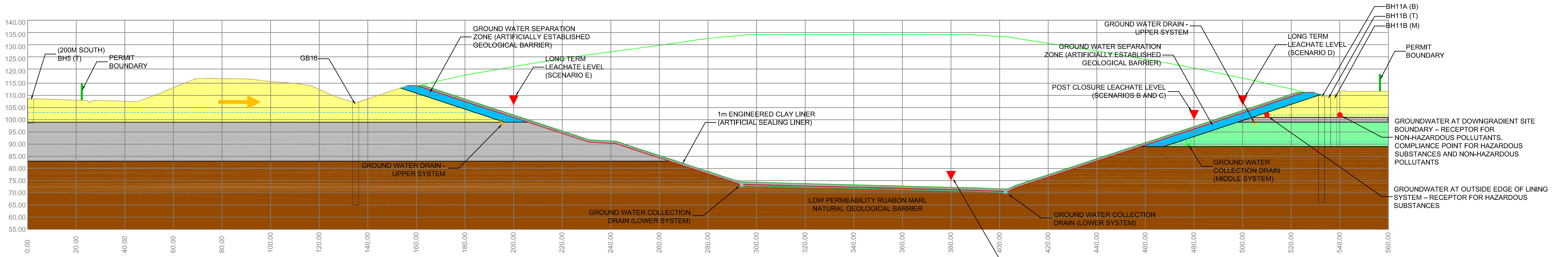
Drawing number

HAF128

Hydrogeological Risk Assessment Scenarios

Scenario	Landfill Source Assumptions	Landfill Cap Assumptions	Drainage System Assumptions	Artificial Liner Assumptions	Assumptions for Dilution in Groundwater
Scenario A (Operational) Advective Migration through Landfill Base into Groundwater Management System	Site specific leachate quality	Operational Infiltration 498mm Following capping and restoration: 50mm	Outward leachate head, with leachate levels up to 2 m above landfill base	Lining system comprising minimum 1.0m to 1.15m engineered clay Liner permeability modelled as Min: 6.0 x10^{-11} m/s Mode: 1.2 x 10^{-11} m/s Max: 1.0 x10^{-9} m/s (Log Triangular)	Dilution in groundwater management system for all substances prior to discharge
Scenario B (Post Closure) Diffusive Migration through Landfill Sidewall into Upper Ruabon Limestone	Site specific leachate quality	Infiltration not used in diffusion modelling	Inward gradient, with leachate levels up to 1m below rebounded groundwater		Dilution of Non-Hazardous Substances in groundwater flow in Upper Ruabon Limestone
Scenario C (Post Closure) Diffusive Migration through Landfill Sidewall into Sand and Gravel Aquifer	Site specific leachate quality	Infiltration not used in diffusion modelling	Inward gradient, with leachate levels up to 1m below rebounded groundwater		Dilution of Non-Hazardous Substances in groundwater flow in Sand and Gravel Aquifer
Scenario D (Long Term Post Closure) Advective Migration through Landfill Sidewall into Upper Ruabon Limestone	Site specific leachate quality	Infiltration includes 50mm/yr through capping and 130mm/yr due to groundwater inflows through sidewalls until leachate rebound	Outward leachate head, with leachate levels up to 4 m above groundwater levels		Dilution of Non-Hazardous Substances in groundwater flow in Upper Ruabon Limestone
Scenario E (Long Term Post Closure) Advective Migration through Landfill Sidewall into Sand and Gravel Aquifer	Site specific leachate quality	Infiltration includes 50mm/yr through capping and 130mm/yr due to groundwater inflows through sidewalls until leachate rebound	Outward leachate head, with leachate levels up to 4 m above groundwater levels		Dilution of Non-Hazardous Substances in groundwater flow in Sand and Gravel Aquifer





SECTION A-A

1:1000

NOTES

1. SURVEY INFORMATION PROVIDED BY SOUTH STAFFS SURVEYS DRAWING REF: 4989b, DATED 12-13/06/2008.

2. BOREHOLE 5 EXTRAPOLATED ONTO THE SECTION FROM IT'S LOCATION APPROXIMATELY 200m SOUTH OF SECTION LINE MARKER.

3. BOREHOLES 11A AND 11B EXTRAPOLATED ONTO THE SECTION FROM THEIR LOCATION APPROXIMATELY 150m SOUTH OF SECTION LINE MARKER.

LEGEND - PLAN

🟩	PERMIT BOUNDARY
— — —	PHASE BOUNDARY
🟦	SURFACE WATER LAGOON
—	SURFACE WATER COLLECTION DITCH
—●—	BASAL GROUNDWATER COLLECTION DRAIN AND SUMPS
—●—	LIMESTONE GROUNDWATER COLLECTION DRAIN AND SUMPS
—●—	SHALLOW GROUNDWATER COLLECTION DRAIN AND SUMPS
A	SECTION MARKER
⊕	GAS MONITORING BOREHOLE
⊕	GROUNDWATER MONITORING BOREHOLE
▪	SURFACE WATER MONITORING POINT
▪	LEACHATE SUMP
⊕	LEACHATE MONITORING BOREHOLE
93.61m	GROUNDWATER LEVEL IN SAND AND GRAVEL (AUGUST 2009)
90.70m	GROUNDWATER LEVEL IN UPPER RUABON LIMESTONE (AUGUST 2009)
92.49m	GROUNDWATER LEVEL IN RUABON MARL (AUGUST 2009)
➘	INFERRED DIRECTION OF SHALLOW GROUNDWATER FLOW

LEGEND - SECTION

—	FORMATION LEVEL
—	PRESETTLEMENT LEVEL
🟨	SAND AND GRAVEL
⬜	BOULDER CLAY
🟩	UPPER RUABON MARL LIMESTONE
🟫	MIDDLE/LOWER RUABON MARL
- - -	CURRENT INFERRED GROUNDWATER LEVEL
→	INFERRED GROUNDWATER FLOW DIRECTION

CORY ENVIRONMENTAL

SLR

4 THE ROUNDAL
RODDINGLAW BUSINESS
PARK, GOGAR
EDINBURGH. EH12 9DB
T: 0131 335 6830
F: 0131 335 6831
www.slrconsulting.com

HAFOD LANDFILL

HRA REVIEW

HYDROGEOLOGICAL CONCEPTUAL SITE MODEL

HRAR1

Scale	Date
1:2,500@A1	MARCH 2010







TerraConsult

Leaders in waste management environmental & ground engineering consultancy

TerraConsult (South) Limited
Dugard House
Peartree Road
Colchester, Essex
CO3 0UL

Tel: +44 (0) 1206 585600

TerraConsult Limited
Bold Business Centre
Bold Lane, Sutton
St. Helens
WA9 4TX

Tel: +44 (0) 1925 291111
Fax: +44 (0) 1925 291191

Email: mailbox@terraconsult.co.uk
Website: www.terraconsult.co.uk

FS 573193

EMS 573194

TerraConsult