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Thorpe Marsh Landfill (EPR/CP3091SC/V002)

Hydrogeological Risk Assessment

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Hydrogeological Risk Assessment

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Contents

Table of Tables

Table of figures

Appendices

Appendix 1
Figures

Appendix 2
Stirling Maynard Drawings

Appendix 3
Screened Dataset

Appendix 4
Combined Dataset

1. Introduction

1.1 Brief

As part of our ongoing support to Thorpe Marsh Green Energy Hub Limited ("TMGEHL" or herein the "Client"), Ramboll UK Limited ("Ramboll") have produced a Hydrogeological Risk Assessment ("HRA") for Thorpe Marsh landfill (the "site"). The landfill is to be redeveloped into a Battery Energy Storage System ("BESS"), and the design works are ongoing.

This HRA is produced with consideration to the Landfill Environmental Permits guidance[1] and Land Contamination Risk Management (LCRM)[2] published by the Environment Agency (EA) in 2021.

The site is located to the west of the former Thorpe Marsh Power Station (which was active between 1963 and 1994), approximately 6km north of Doncaster town centre. The approximate centre of the site is at National Grid Reference (NGR) 459480, 409490. A Site Location Plan is provided in Figure 1, Appendix 1.

1.2 Proposed Development and Site Background

Thorpe Marsh Landfill is a regulated waste disposal site covered by an Environmental Permit (Waste Management Licence (WML) number WD20D53, originally granted in 1977, now EPR/CP3091SC/V002). The permit allowed the disposal of predominantly pulverised fuel ash (PFA) as well as domestic, commercial and industrial wastes from the adjacent Thorpe Marsh Power Station disposed discretely in areas that will not be disturbed by the proposed re-development. The landfill was operated prior to the implementation of the 2001 Landfill Directive (LfD) and was designed as a 'dilute and disperse' land-raise landfill. The waste disposal cell was formed by the construction of a three sided, 'U' shaped ("horseshoe") bund using PFA. Within the cell, the PFA waste was co-disposed with other permitted waste types within the southern end of the site. The early closure of the Power Station in 1994 resulted in the cell being only partially infilled and the landfill put into closure. However, the landfill's environmental permit was not surrendered.

The current permit holder is HJ Banks and Company Ltd. A permit transfer application has been submitted (ref. EPR/CP3091SC/T002) to transfer the permit to Thorpe Marsh Green Energy Hub Limited. This transfer application is to be decided alongside the proposed permit variation application.

The proposed redevelopment of the landfill into a BESS will involve submission of a permit variation application for re-opening of the landfill to facilitate creation of a development platform using re-profiling of PFA from both the eastern and western arms of the 'U' shaped bund.

It is understood that PFA is not considered to be inert (email from Helen Culshaw of the Environment Agency dated 9th October 2023) and therefore the LfD standards for hazardous or non-hazardous wastes[3] would apply. However, it was stated that some standards (including the specification of the lining and leachate collection system) could be reduced or removed based on a risk assessment and this aligns with the EAs landfill guidance[4] that allows sustainability to be considered in the design of landfill cells:

- *"Sustainability: demands that on-site or local materials are used where feasible. The Environment Agency actively encourages the use of low-grade materials, processed to make them acceptable, in appropriate situations within landfills"*

The intent of this HRA is to further demonstrate that PFA can be relocated on-site to form a development platform for the BESS and result in a negligible risk to the environment. This will allow the construction of the BESS in a more sustainable and low carbon manner compared to importing significant quantities of materials to form a fully designed landfill cell. This report assesses whether the proposals are suitable and the nature of potential impacts.

[1] Landfill operators: environmental permits - What to include in your hydrogeological risk assessment - Guidance - GOV.UK (www.gov.uk)
[2] Land contamination risk management (LCRM) - GOV.UK (www.gov.uk)
[3] Landfill operators: environmental permits - Design and build your landfill site - Guidance - GOV.UK (www.gov.uk)
[4] LFE4 - Earthworks in landfill engineering, Environment Agency, LFE4_earthworks_on_landfill_sites.pdf (publishing.service.gov.uk)

The original permit installation boundary drawing associated with WML number WD20D53 is shown on Figure 2, Appendix 1. The total permit site area extends to approximately 61 Ha (hectares). This includes c.17 Ha of land to the west which is currently occupied by the Thorpe Marsh Nature Reserve and the eastern 44 Ha comprises the former Thorpe Marsh Power Station pulverised fuel ash (PFA) landfill. The landfill plot is unsurfaced and is mostly covered by naturally regenerating grassland and some small areas of scrub / woodland. The outer flanks were spread with thin layer of topsoil historically and there are isolated areas of hard standing and surfaced roads.

The site topography is dominated by the deposited waste and in particular a U-shaped bund covering much of the site area. The site levels vary between approximately 0m AOD in the south of the site to 24 m AOD at the top of the bund. A topographical survey was undertaken in February 2024 and is presented as Figure 3, Appendix 1.

The site lies in a predominantly agricultural setting with the village of Barnby Dunn located from 1.5km to the east. The former Thorpe Marsh power station lies directly east of the site and a raised river, the EA Beck, runs in a manmade channel near the south of the site.

1.3 Objectives and Scope

The HRA detailed in this reported has been prepared by Ramboll in support of the Permit variation application. The HRA is based on data and information contained within the Conceptual Site Model (CSM) report[5] and Environmental Setting and Installation Design[6] report, which should be read in conjuncture with the HRA.

The scope of the HRA report has included the following:

- Summary of the conceptual site model;
- Hydrogeological risk assessment modelling to quantify:
  - potential risks presented by the new landfill cell.
  - sensitivity of the surrounding water environment.
  - hazards posed and the likelihood of potential risks happening.
- Assessment of risks to the water environment at different stages of the site’s lifecycle;
- Identification of potential for changes to ground conditions due to weather conditions and seasonal/climatic patterns and how these changes may affect the CSM;
- Assessment of technical precautions in conjunction with any natural geological barriers or attenuating layer; and
- Conclusions, presented to:
  - confirm that the new landfill cell meets the relevant standards of the Environmental Permitting Regulations 2016 schedules 9, 10, 21 and 22, as appropriate;
  - confirm that the design of the new landfill cell will prevent unacceptable discharges and emissions over the entire lifecycle of the new landfill cell; and
  - propose compliance limits and assessment levels for leachate, groundwater and surface water, where applicable.

1.4 Constraints and Limitations

This report has been prepared by Ramboll exclusively for the intended use by the client in accordance with the agreement between Ramboll and the Client defining, the purpose, the scope and the terms and conditions for the services. No other warranty, expressed or implied, is made as to the professional advice included in this report or in respect of any matters outside the agreed scope of the services or the purpose for which the report and the associated agreed scope were intended, or any other services provided by Ramboll.

In preparation of the report and performance of any other services, Ramboll has relied upon publicly available information, information provided by the client and information provided by third parties.

[5] Thorpe Marsh Landfill (EPR/CP3091SC), Conceptual Site Model Report, Ramboll UK Ltd, reference REH2023N03018-RAM-RP-00009_CSM, dated May 2024.
[6]

Accordingly, the conclusions in this report are valid only to the extent that the information provided to Ramboll was accurate, complete and available to Ramboll within the reporting schedule.

Ramboll's services are not intended as legal advice, nor an exhaustive review of site conditions and/or compliance. This report and accompanying documents are initial and intended solely for the use and benefit of the client for this purpose only and may not be used by or disclosed to, in whole or in part, any other person without the express written consent of Ramboll. Ramboll neither owes nor accepts any duty to any third party, unless formally agreed by Ramboll through that party entering into, at Ramboll's sole discretion, a written reliance agreement.

Unless otherwise stated in this report, the scope of services, assessment and conclusions made assume that the site will continue to be used for its current purpose and end-use without significant changes either on-site or off-site.

2. Conceptual Hydrogeological Site Model

This section discusses the detailed conceptual groundwater model for the site, designed to quantitatively assess the risks posed to the identified pollutant linkages defined in the CSM (May 2024).

The CSM report qualitatively identified a potential source-pathway-receptor relationship from the leaching of contaminants associated with the relocated PFA to on-site groundwater resources, albeit this was considered likely to have a negligible impact given the dilute and disperse nature of the existing landfill design, the PFA had already been exposed to decades of rainfall and that leachate test data from a recent ground investigation in 2024 had not identified significant exceedances of Potential Contaminants of Concern typical of PFA.

2.1 Geology

A ground investigation was undertaken between January and March 2024 (as discussed within the CSM) which identified Made Ground and PFA across the site. The thickness of the Made Ground and PFA was noted to range between 0.8m bgl/6.96m above ordnance datum (AOD) (RBH146) and 24.5m bgl/0.13m AOD (RBH124), due to the raised nature of the PFA landfill. Made Ground was largely confined to the discrete area in the south of the landfill that was subject to co-disposal of PFA and commercial waste from the power station; this area is not proposed to be disturbed by the PFA relocation activities. Therefore, the assessment herein focusses on PFA and its properties.

The greatest thickness of PFA deposits are associated with the PFA U-shaped bund located in the east, south and west of the site. The thickness of the Made Ground and PFA deposits are depicted in Figure 4, Appendix 1.

According to BGS records, the site is directly underlain by the Hemingbrough Glaciolacustrine Formation (Clay, Silty, Unproductive Strata) on site, and, off-site, Alluvium (Clay, silt, sand and gravel, Secondary Aquifer) immediately east of the site, parallel to the Thorpe Marsh Drain.

The Hemingbrough Glaciolacustrine Formation was identified within the boreholes across the entirety of the site encountered at a depth of between 0.8m bgl/6.96m AOD (RB146, north) and 24.5m bgl/0.13m AOD (RB124, southern area of bund).

The thickness of the superficial deposits was notably found to be thicker in the south-east and in the north-west of the site area and was generally over 10m thick across the site though reduced to ~4-5m thickness on the eastern side of the landfill. This is depicted in Figure 5, Appendix 1.

BGS records indicate that the superficial deposits are underlain by bedrock geology of the Chester Formation (Sandstone, pebbly / gravelly), part of the Sherwood Sandstone Group. The Chester Formation was encountered in the 2024 investigation from depths of between 10.5m bgl/ -2.06m AOD (RBH113, north-east) and 33.0m bgl/ -10.16m AOD (RBH129, west). Boreholes drilled in 2021 indicated that the bedrock unit was encountered at even greater depths of 40.70 m bgl (MW7S) in the north-west of the site and of 71.50 m bgl / -60.1 m AOD (MW4S) in the south-east. The depths to the Chester Formation are presented in Figure 6, Appendix 1. This variation in rockhead may relate to the presence of an infilled glacial channel that is known to run through this location and is identified as the Barnaby Dunn Station Channel on BGS resources. However, this does not appear to be causing a significant influence on groundwater flow directions based on the groundwater contour plots in the CSM report.

2.2 Hydrogeology and Hydrology

2.2.1 Hydrogeology

Groundwater flow within the PFA, drift and bedrock deposits exhibit similar patterns, with groundwater within the PFA generally depicting a southerly flow direction with local variation and some component of flow to the east, and groundwater within the drift exhibiting a similar pattern. This accords with the anecdotal description of the original construction of the PFA landfill with a drainage blanket intended to control groundwater flow to the south and east towards toe drains located at the base of the landfill slope on the southern and eastern sides, as discussed in the hydrology section below. There is a potential for localised connectivity between the PFA and drift deposits particularly as shallow drift was previously excavated prior to deposition of PFA which may have resulted in more permeable bands of drift being exposed. Groundwater contour plots are provided in the CSM report.

Groundwater in the sandstone is semi-artesian in nature and confined below the drift deposits. This is expected to provide a degree of protection from the vertical migration of on-site contaminants and to limit the potential for significant mixing of groundwater bodies.

It is understood that the regional groundwater flow within the Principal Aquifer is generally to the east, influenced by the presence of groundwater abstractions wells located approximately 370m east of the site and utilised for general industrial (by National Power Plc – however, this is assumed to relate to the former power station activities and is now assumed to be redundant). The site lies towards the edge of the overall Source Protection Zone (SPZ) III and the nearest abstraction points associated with the SPZ are all located from over 2km distant to the east.

Groundwater monitoring has been undertaken since May 2021 by Egniol and indicates that groundwater levels recorded within wells targeting the PFA, drift and bedrock deposits have been recorded at similar elevations ranging from 10m AOD to 5m AOD within the PFA, 7m AOD to 1m AOD within the drift deposits and 6m AOD to 1m AOD within the bedrock. As such, it has been considered for the purpose of this HRA that the three waterbodies are potentially in hydraulic continuity.

2.2.2 Hydrology

No significant water courses are present on-site; however, a series of drains (finger drains) are present around the perimeter of the site which discharge into the toe drains at the base of the slope of the landfill along the southern and eastern extent.

Two (2) toe drains are present in the south and east of the site located adjacent to each other and discharging from the first drain into the second. Based on the ground elevation along the drains, the surface water within the closest drain is expected to be between -0.7 and -0.28m AOD and the second drain around -0.62m AOD.

A previous report[7] indicated that the southern part of the site is underlain by a drainage blanket which drains on-site groundwater into the toe drains via short finger drains in the south-east of the mound and a drainage pipe in the south-west. Most or all recharge (infiltrating rainfall) falling within the landfill U shaped bund flows south through the PFA and exits into the toe drain via either the drainage pipe, the finger drains or a spring line at the base of the PFA. The CSM report found that the PFA groundwater levels dip to the south, indicating that most of the generated PFA groundwater is directed towards the toe drains.

The nearest significant watercourse to the site is the Thorpe Marsh Drain (also known as Ea Beck) located 30m east of the site at its nearest point, understood to flow south-west to north-east though is known to be slow moving. The Thorpe Marsh Drain is a raised levee and discharges into the River Don approximately 1.1km to the north-east.

The toe drain may have historically been connected to an adjacent pumping station, to discharge into the Thorpe Marsh Drain, albeit the end of the toe drain is silted and no obvious connection pipe was identified during walkovers or a dye test.

2.3 Contaminant Source

The contaminant source is defined for this assessment as the new landfill cell formed when creating the development platform using re-profiled PFA from the eastern and western arms of the ‘U’ shaped bund.

The new cell will be formed of PFA that was deposited by the previous power station activities and comprised finer fly ash that was reportedly dampened and discharged into lorries, before it was taken to the station ash

[7] Geraghty & Miller International Inc, 1994. Hydrogeological Investigation and Waste Disposal Assessment Main Technical Report. Dated: September 1994.

fields (i.e., the landfill). Initial ash deposition is shown to be in the north-east of the site only on mapping between 1966 and 1980), with deposition in the south shown in mapping from 1982 onwards.

As discussed above, and within the CSM report, PFA is encountered across the majority of the site area and has been exposed to surface water run-off and infiltration to the associated discharge point (toe drains) for decades. Therefore, readily leachable substances are expected to have already been released to ground, which is evident from the available chemical data discussed herein.

The UK Quality Ash Association states that PFA is a:*" low permeability, pozzolanic material (i.e. becomes cementitious when exposed to water) and can be used to contain contaminants in brownfield sites thus preventing leaching from contaminated waste".* The UKQAA further states that PFA has a water-soluble content of less than 1%, the majority of which is gypsum[8].

In general, PFA consists primarily of silicon dioxide (SiO_2), aluminium oxide (Al_2O_3), and iron oxide (Fe_2O_3). The exact composition can vary depending on the source of coal but can include trace heavy metals including cadmium, nickel, vanadium, zinc, lead and magnesium and sulphur[9].

Studies focussed on the environmental risks from the development of PFA fill earthwork structures have highlighted the potential for PFA to leach residual contaminants to the environment[10]. This noted that two phases of leaching have been recognised in fresh unbound PFA fill; an initial phase, where elements are leached from the surface of the PFA particles and a secondary phase, where elements are released from the glass matrix. Ca, Na, K and SO4 are readily available in the initial stages of leaching. Other elements typically released from the particle surfaces during the initial phase also include B, Cd, Cl, Cu, Fe, Hg, Mn, Pb, Ti and Z. Determinands such as Ca, Pb and Zn are released in a secondary phase which takes place over a longer time period. Ca, K, Na and SO4 appear to be released throughout both initial and secondary leaching phases. Leaching tests on weathered PFA show that the leaching of certain elements continues at low dissolution rates over long time periods, and this is the core focus for this HRA given the PFA has been exposed to the elements for a significant period.

In this context, PFA is a well understood material, is commonly used in earthworks and there is an existing testing program in place under the current WML. To support this HRA and the development of the new landfill cell and BESS project, a ground investigation (GI) was undertaken between 29th January and 4th March 2024 and comprised twenty-two boreholes and twenty-seven machine excavated trial pits. This report and associated documents provide interpretation of the information generated by the GI.

The testing suite for samples of PFA focussed on the following potential contaminants of concern, noting that not every trace element that may exist in PFA was tested with the following considered to be suitable from an environmental risk perspective:

- pH
- Sulphate as SO4
- Total Sulphur
- Chloride
- Ammoniacal Nitrogen as NH3
- Nitrate as N
- Nitrite as N
- Aluminium, antimony, arsenic, boron, cadmium, chromium, iron, lead, manganese, molybdenum, selenium, vanadium
- Calcium, magnesium, potassium, sodium

[8] https://www.ukqaa.org.uk/wp-content/uploads/2014/02/Datasheet_2-0_May_2007.pdf

[9] Kar, K.K. (2022) Handbook of fly ash. Oxford: Elsevier.

[10]https://www.bing.com/ck/a?!&&p=fcabede13aefa55fJmltdHM9MTcxNjk0MDgwMCZpZ3VpZD0zOTA0ZjRlMC0wYWFhLTZkZGUtMDM5NC1lN2I5MGI5MjZjNWUmaW5zaWQ9NTIwNw&ptn=3&ver=2&hsh=3&fclid=3904f4e0-0aaa-6dde-0394-e7b90b926c5e&psq=NVIRONMENTAL+RISK+FROM+THE+DEVELOPMENT+OF+PFA+FILL+EARTHWORK+STRUCTURES+AND+AN+IMPROVED+CODE+OF+PRACTICE+TO+MITIGATE+POTENTIAL+IMPACT&u=a1aHR0cHM6Ly9vbmxpbmVsaWJyYXJ5LndpbGV5LmNvbS9kb2kvYWJzLzEwLjEwMDIvbGRyLjEwNDE&ntb=1

In addition, to further evidence the waste status, waste acceptance criteria testing was performed for solid waste and eluate analysis as follows:

- **Solid waste**: total organic carbon, loss on ignition, benzene toluene, ethylbenzene and xylenes, sum of polychlorinated biphenyls, total polycyclic aromatic hydrocarbons, pH, acid neutralisation capacity.
- **Eluate**: arsenic, barium, cadmium, chromium. Copper, mercury, molybdenum, nickel, lead, antimony, selenium, zinc, chloride, fluoride. Sulphate, total dissolved solids, phenols (monohydric) and dissolved organic carbon.

It is estimated that approximately 600,000 m^3 of PFA will be excavated and redeposited to form the new landfill cell. Ground models based on previous phases of intrusive investigation estimate that there is a total of approximately 4.4 million m^3 of PFA within the current permit boundary. As such, the new landfill cell will be formed of approximately 13% of the total PFA volume present on the site.

The location, size, depth and shape of the areas of PFA excavation and the new landfill cell are presented in Appendix 2.

Existing PFA was deposited up to nearly 50 years ago and no new waste is to be accepted as part of the proposed permit variation. Therefore, the new landfill cell is not considered likely to produce additional significant quantities of leachate, particularly given the historical exposure to rainfall and infiltration since deposition. However, as noted above, there is a potential for PFA to leach certain constituents throughout its lifetime. This HRA focuses on the potential leaching of PFA once emplaced as part of the new landfill cell. The relocation of the PFA during the proposed earthworks will also need appropriate controls to manage short terms environmental risks associated with dust, noise, surface water run-off etc, which will be managed through a Construction Environmental Management Plan ("CEMP") and detailed method statements prepared by the appointed earthworks contractor in accordance with good practice industry techniques. Therefore, this HRA focuses on the longer-term leaching potential including potential climate change effects.

The leachable substances anticipated from the new cell materials are assumed likely to have the same chemical characteristics as the soil leachability data obtained from these materials by the recent site investigation, although as noted the majority of leaching has likely already occurred and peak leachate concentration is already likely to have been reached in the landfill as baseline conditions.

Soil leachate data from the 2024 investigation has been provided and discussed in the CSM report. The data has been assessed in accordance with the framework for non-hazardous and hazardous substances provided in the Water Framework Directive (WFD). The WFD requires prevention of input of hazardous substances to the groundwater and limit of non-hazardous input to groundwater. The UK hazardous substances to groundwater are based on the UKTAG Technical Report on Groundwater Hazardous Substances (September 2016) and the accompanying Hazardous Substances List (January 2018). Should the hazardous substances be detected above the Minimum Reporting Values (MRV) they should be assessed further. Non-hazardous substances are assessed using risk based generic assessment criteria (GAC) defined based on the receptors of concern. For this assessment, it is assumed there is a potential surface water receptor and groundwater resource receptor.

The full dataset screened against GAC and MRV is provided in Appendix 3 and contaminants above the GAC/MRV in one or more samples are summarised in Table 2.1 below.

Table 2-1 - Soil Leachate GAC Exceedance; New Landfill Cell Summary

Analyte	No. of Samples Results	GAC / MRV	No. of GAC Exceedances	Material Type	Max Conc (µg/l)
Sulphate as SO_4	17	250*	11	PFA	1,590
		400**	4		
Antinomy	7	5.0*	1	PFA	8.1
Arsenic	17	10*	12	PFA	69
		50**	4		
		1 (MRV)			
Chromium	17	50*	0	PFA	13
		4.7**	4		
Bioavailable Copper	10	1***	1	PFA	1.04
Lead	17	10*	0	PFA	2.5
		1 (MRV)	5		
Mercury	10	1*	0	PFA	<0.5
		0.07**	0		
		0.01 (MRV)	10		
Manganese	2	50*	1	PFA	78
Selenium	17	10*	4	PFA	33
Vanadium	10	20**	1	PFA	29
Naphthalene	4	0.075*	1	PFA	0.96

* Groundwater resource potential - risk based standards to protect potable water supply potential
** Freshwater AA EQS
*** Bioavailable GAC

For hazardous substances the minimum reporting values (MRV) were used as the GAC and exceedances were limited to heavy metals including arsenic and lead. Although it was noted that the MRV (0.01 µg/l) for Mercury was lower than the laboratory detection limit (0.5µg/l) and as such mercury has been carried forward as a potential source contaminant as a precautionary assessment.

In order to create a larger, more representative sample set, the soil analytical data was considered further. This included forming paired datasets from the leachate and soil data and comparing the concentrations of each of the CoPC, as discussed above, to calculate a multiplier. The multiplier represents an estimate of the typical fraction of the total to be assumed mobile based on the measured eluate concentrations.

This multiplier is then used to calculate estimated likely leaching values for each compound of concern from the soil data to then combine with the measured eluate data to form a combined dataset to be considered for statistical analysis. This combined dataset is considered to provide a representative reasonable worst-case estimation for average leachable contaminant concentrations throughout the PFA. The combined dataset is presented in Appendix 4.

The 90% upper confidence interval for the mean (90% UCI) is used as a reasonable worst-case estimate for the mean at this stage. Where this 90% UCI is below the GAC, the CoPC is no longer considered a risk. Compounds which have a 90% UCI higher than the GAC are taken through to further detailed QRA modelling as discussed further in Section 3.6.

Table 2-2 - Statistic Analysis of Combined Dataset for CoPC

Analyte	Minimum Assessment Criteria	Units	Average	90% UCI	Exceedance of the criteria?
Antimony	5	µg/l	2.58	3.19	No
Arsenic	1* (leachate MRV)	µg/l	26.5	31.4	**Yes**
Chromium (Cr III)	4.7	µg/l	1.88	2.53	No
Copper (bioavailable)	1 (bioavailable GAC)	µg/l	0.49	0.67	No
Manganese	50	µg/l	21.6	30.2	No
Mercury	0.01 (EA MRV)	µg/l	<0.5	<0.5	**Yes****
Lead	1* (leachate MRV)	µg/l	1.23	1.48	**Yes****
Sulphate	250	mg/l	292	380	**Yes**
Selenium	10	µg/l	6.64	8.16	No
Vanadium	20	µg/l	19.2	22.7	**Yes**

* In the absence of published values, the laboratory method reporting limit has been used.
** Included as precautionary assessment. All mercury data below lab detection limit, however this was significantly higher than the EA's MRV so included as a precautionary assessment.

The data provided in Table 2.2 is considered representative of potential contaminants of concern in the new cell source material. This material as noted in Section 2.3 accounts for approximately 13% of the original volume of landfill waste. Leachability data available for unsaturated zone waste materials to remain in situ indicates similar or slightly greater concentrations of the Contaminants of Concern (CoC) in the remainder of the landfill. There is also existing contamination of groundwater and surface waters that form the baseline conditions, as described below.

2.4 Pathways and Receptors

The 2024 CSM identified potential pollutant linkages across the site including:

- Groundwater receptor: leaching from waste into shallow groundwater in the landfill followed by further vertical and lateral migration through the superficial deposits (unproductive strata) into the bedrock Principal Aquifer.
  - Surface water receptors: Leaching from waste into shallow groundwater followed by lateral migration to the toe drains, albeit no direct groundwater pathway to the EA Beck (via groundwater) was identified.

2.4.1 Groundwater Connectivity

As discussed above, groundwater has conservatively been considered to be in hydraulic continuity between PFA, drift and sandstone water bodies, although for the latter there was considered to be limited potential for connectivity given the low permeability nature of the drift, depth to rockhead and the semi-artesian pressure of the sandstone across much of the site limiting the potential for groundwater mixing.

Elevated chemical concentrations recorded within the groundwater beneath the site confirm that the groundwater within the drift deposits has been previously impacted from the existing landfill. However, concentrations of contaminants are noted to be significantly lower in the sandstone groundwater body indicating that the low-permeability superficial drift deposits are limiting the migration of impacted groundwater to the underlying Principal Aquifer. As such, the groundwater pathway is considered to be vertical leaching from the waste into shallow groundwater within the landfill and lateral migration of shallow groundwater off-site potentially to the Secondary aquifer and Sandstone Principal Aquifer off site.

A summary of groundwater analytical data from the 2021-2024 groundwater monitoring is provided in Table 2.3 below showing average/typical groundwater concentrations in comparison to the average leachable concentrations of the CoC in the Source material.

Table 2-3 – Summary of Groundwater Data

Analyte	Minimum Assessment Criteria	Units	Average from soil leachability analysis	Drift GW Average	Sandstone GW Average
Arsenic	1* (leachate MRV)	µg/l	27	21.3	1.17
Mercury	0.01 (EA MRV)	µg/l	<0.5	0.26	0.05
Lead	1* (leachate MRV)	µg/l	1.23	0.21	0.32
Sulphate	250	mg/l	292	1480	231
Vanadium	20	µg/l	19	31.7	0.38

Arsenic was detected in all soil leachability analyses, with an average concentration slightly higher than the concentrations recorded within the drift groundwater.

Mercury was below detection limits in all the soil leachability analyses, however the detection limit was higher than that achieved in the groundwater analysis and higher than the MRV. Mercury has therefore been included as a precautionary assessment due to the recorded exceedances of the MRV within the groundwater.

The majority of groundwater samples from the drift deposits and soil leachability samples recorded lead below the detection limit, therefore the averages have been skewed where the detection limit has been used for the purpose of statistics. This has been included as a precautionary assessment.

Both sulphate and vanadium recorded concentrations in the soil leachability analysis which were lower than that recorded within the drift deposits. This indicates that the background concentrations are already elevated due to historic leaching from the landfill, and as such the potential of the PFA to be moved in the new cell to increase contaminant loading to the drift groundwater body is very low.

All of the CoC, with the exception of lead, recorded lower concentrations within the sandstone groundwater than the drift groundwater providing further evidence that the superficial deposits are acting as an aquitard preventing the vertical migration of contaminated groundwater between the drift and the sandstone beneath the site.

2.4.2 Surface Water Connectivity

Surface water sampling was undertaken in the surface water bodies located on or adjacent to the site including the ponded waters, toe drains, outer drains and Thorpe Marsh drain. Within the inner toe drains elevated concentrations of contaminants were recorded with a contaminant profile broadly similar to that observed within the leachate data. As discussed within the CSM, this indicates that there is a pathway between the shallow PFA groundwater and the toe drains in the south of the site. However, the outer drain and Thorpe Marsh drain are observed to have a different chemical signature suggesting that it is not being impacted by the PFA derived leachate.

The observed difference in chemical signatures across the surface water bodies supports the current understanding of the site drainage, with surface water runoff, and drainage from the PFA through the finger drains and toe drains. The chemical signature in Thorpe Marsh Drain does not indicate any impact from the site leachate; this supports the evidence there is a lack of connection between the toe drains and Thorpe Marsh drain. It is therefore considered that the toe drains are effectively acting as a hydraulic barrier, with the potential for collected leachate to locally migrate laterally and vertically into the drift deposits rather than laterally into other local surface water courses.

In summary, on-site groundwater in the PFA is likely to be in connectivity with the toe drains but there is no clear evidence of a direct pathway to the nearby surface water courses. The surface water bodies are at a higher elevation than the groundwater on site thus potential impact to surface water via groundwater flow would not be anticipated near to the site. There is no evidence that the toe drains are connected to the pumping station.

3. Hydrogeological Risk Assessment

3.1 Legislative Context

3.1.1 Landfill Directive

The existing landfill was operated under a WML granted in 1977 and is of a dilute and disperse construction. The proposed movement of PFA will create a new landfill cell which will be subject to conditions of the LfD[11][12] The overall aim of the LfD is to prevent or reduce as far as possible negative effects on the environment, in particular the pollution of surface water, groundwater, soil and air, and on the global environment including the greenhouse effect, as well as resulting risks to human health, from landfilling of waste, during the whole life-cycle of the landfill.

Guidance for the implementation of the LfD[13] indicates that an environmental risk assessment should be undertaken in accordance with[14]

a. prevent the input of any hazardous substance to groundwater; and
b. limit the input of non-hazardous pollutants to groundwater so as to ensure that such inputs do not cause pollution of groundwater.

3.1.2 Water Control and Leachate Management

The collection of contaminated water and leachate is not required if the landfill poses no potential hazard to the environment, as shown by the site's environmental risk assessment. 'No potential hazard' in this context means there is no likelihood of an unacceptable discharge over the entire lifecycle of the site. If the quantity or quality of any leachate produced by the waste is insignificant or if there is no identified pathway or receptor for contamination, then the collection of leachate is unnecessary and a sealing liner is not required.

3.1.3 Protection of Soil and Water

Landfills must be situated and designed to prevent pollution of the soil, groundwater or surface water and ensure efficient collection of leachate as and when required. The protection of soil, groundwater and surface water is to be achieved by the combination of a geological barrier and a basal liner during the operational phase, and by the combination of a geological barrier and a top liner after closure.

Paragraph 3.4 of Annex I to the Directive provides for the reduction of the requirements in the geological barrier, basal liner and top liner in two situations based on the environmental risk assessment:

a. if collection and treatment of leachate is not necessary; or
b. if it has been established that the landfill poses no potential hazard to soil, groundwater or surface water.

'No potential hazard' in this context means that the environmental risk assessment demonstrates that the reduction of the requirements will result in an acceptable risk to soil and water.

There are circumstances where the requirements of Paragraph 3.1 (i.e., a geological barrier, basal or top liner) are not needed to meet the overall objective of the Directive, and in particular the purpose of paragraph 3.1 - the protection of soil and water.

In order to remove the requirement for one or more of a geological barrier, basal or top liner, the environmental risk assessment must show that a particular requirement would provide a negligible contribution to the protection of soil and water. 'Negligible contribution' means that the necessary conditions were in place to protect soil and water and the addition of the barrier or liner in question would add little or nothing to environmental protection.

[11] European Community (EC) Directive 1999/31/EC on the landfill of waste (the Directive).

[13] Environmental Permitting Guidance, The Landfill Directive, For the Environmental Permitting (England and Wales) Regulations 2010, Department for the Environment, Food and Rural Affairs, dated March 2010.

3.2 Landfill Design Considerations and Scenarios

3.2.1 Proposed Installation Design

The new landfill cell will comprise an area of 26.1 hectares, with thicknesses of PFA in the new cell ranging from between 0.0 m (where the new cell will be formed by excavation into existing slopes) and 9.9m at its deepest point. The new landfill cell will only contain PFA waste.

PFA will be deposited in approximately 225 mm thick layers and compacted to reduce future settlement. Stability and settlement risk assessments indicate that the design of the landfill is sufficient to form the development platform for the BESS and PFA slopes will be stable. The final new landfill cell elevations will vary between 0 metres bgl and 9.9 m bgl, with the landfill cell having a general sloping surface towards the south-west to aid surface water run-off.

Based on the recorded leachate and groundwater contaminant concentrations, discussed in Section 2.3 and the CSM, the PFA within the new landfill cell is not considered to create a new significant source of contamination.

Given the lack of a significant contaminant source and the existing elevated baseline conditions the new landfill cell is considered to have a negligible impact on existing background groundwater and surface water conditions over the cell's lifetime.

As the proposed surface water design for the BESS will significantly limit the potential for surface water to infiltrate to the ground, the modelling has been undertaken under the assumption that no collection of leachate is required and that there is no requirement for the installation of a top liner (landfill cap). It is understood that although the new landfill cell will not have an engineered cap, the compacted PFA will act as a low permeability material which will inhibit infiltration and provide improvement compared to the current free draining situation.

The required BESS foundations (likely pre-cast concrete or composite strip foundations), cable ducts and surface water drainage systems will be constructed within the landfill cell, as part of the engineered landfill design. Surface water run-off will be collected and discharged via a series of attenuation ponds to control flow during peak rainfall into the toe drain and then pumped to Thorpe Marsh Drain, subject to further detailed design considerations that are on-going.

3.3 Controlled Waters Assessment Methodology

Detailed risk assessment modelling has been completed to estimate potential risks from the CoCs identified in Section 2.3 given the development scenario detailed in Section 3.2.

The assessment of risks to Controlled Waters has been undertaken using the ConSim model, Version 2.05.0005. The ConSim model was developed on behalf of the Environment Agency (EA) to meet EA guidelines (Environment Agency Remedial Targets Methodology: Hydrogeological Risk Assessment for Land Contamination (2006), R&D20.

ConSim uses probabilistic assessment to model natural uncertainties in ground conditions. These natural variations, such as hydraulic conductivity and thickness of the saturated zone, are input as a range of values. ConSim uses the 'Monte Carlo' approach whereby calculations are completed through numerous iterations for each model run. Each iteration, the value for each input parameter is randomly selected from within the specified range. Each model run gives a range of output values, in a distribution that reflects the uncertainty of the input values. The output from each model run is represented graphically or statistically as a probability distribution of predicted concentrations at the receptor point(s).

ConSim has three tiers of assessment for soils:

- Tier 1, leaching;
- Tier 2, unsaturated zone migration and dilution within the aquifer; and
- Tier 3, migration in aquifer.

Tiers 1 and 2 assess the soil leaching to groundwater. Tier 3 assesses migration of contamination present within groundwater considering the effects of attenuation on groundwater contaminants between the source and a down-gradient receptor (i.e., migration to a designated compliance point), as well as processes which can include dilution, dispersion, retardation and degradation. Tier 3 in ConSim does not allow the application of a declining source or fracture flow within the aquifer.

Although the CSM has identified limited potential for a significant environmental risk Ramboll has completed this DQRA on the basis that the EA HRA guidance states that a DQRA is required for landfills that accept hazardous or non-hazardous waste.

As mentioned previously this HRA focussed on the long-term leaching potential of PFA to be placed in the new cell and ConSim is considered to be suitable for that purpose and to demonstrate the necessary confidence given the stochastic nature of the modelling.

3.4 Model Assumptions and Input Parameters

The modelling has been set up with assumptions around the hypothetical conceptual model (source-pathway-receptor) scenario. This assessment is intended to reflect a reasonable worst-case scenario of placement of PFA material for the reprofiling of the landfill to create a development platform. The key assumptions around this are described below.

3.4.1 Model Generic Assumptions

The following assumptions have been made for the purpose of this DQRA:

- The aquifer units through which contaminants migrate are homogenous and isotropic;
- Groundwater represents a continuous waterbody across the site.
- Groundwater flow is in steady state, and moves in a straight line via the shortest distances towards the compliance point;
- Attenuation of contaminants, where appropriate, includes retardation, degradation, dilution and dispersion within groundwater.
- Linear sorption applies;
- Dispersivities are described by proportion of pathway length as 10% longitudinal, 1% transverse and 0.1% vertical;
- Contaminant sources were modelled as declining sources using the ConSim model calculations, this appears reasonable given the general low leaching potential of the PFA that would be expected to decline over time;
- The ConSim model uses a probabilistic approach and has been run for 1001 iterations; and
- The timeslice assessment within the model has been completed using a logarithmic scale from 1 to 10,000 years.

3.5 Source Characterisation

The priority contaminants to be modelled are based on the findings of the assessment provided in the CSM report, and discussed in Section 2.3, and comprise arsenic, lead, mercury, sulphate and vanadium.

For each contaminant, soil – water partition coefficients are required to help define contaminant behaviour in the subsurface. In the absence of site-specific data, these are sourced from literature and provided in Table 3.1. below.

Table 3-1 - Source Contaminant Concentrations

Analyte	Minimum Assessment Criteria	Units	Average	90% UCI	Partition Coefficient (Kd)	Solubility
Arsenic	1* (leachate MRV)	µg/l	26.5	31.4	500	1250000
Mercury**	0.01 (EA MRV)	µg/l	<0.5	<0.5	500	74000
Lead	1* (leachate MRV)	µg/l	1.23	1.48	1000	296000
Sulphate	250	mg/l	292	380	0	-
Vanadium	20	µg/l	19.2	22.7	12.6	211000

* In the absence of published values, the laboratory method reporting limit has been used.

** Included as precautionary assessment. All mercury data was reported below lab detection limit, however this was significantly higher than the EA's MRV so included as a precautionary assessment.

The 90% UCI for each of the above contaminants were noted to exceed the minimum assessment criteria (DWS, EQS or MRV). As such, these compounds have been taken forward within the detailed risk assessment modelling and the 90% UCI of measured leaching concentrations are used to reflect Tier 1 leaching and provide input concentrations for fate and transport modelling.

Source Area: Approximately 600,000 m^3 of PFA will be excavated from the U-shaped bund and be deposited across the landfill. The location, size, depth and shape of the areas of PFA excavation and the new landfill cell are presented in the cut and fill drawings provided (Appendix 2). The new landfill cell will be filled from the south, moving northwards, in layers approximately 225 mm thick before compaction.

The source area is noted to have a thickness ranging from 1-2m across the majority of the site with areas of increased thickness in the south of the site (up to 9.9m), along the northern site boundary and in the south-eastern corner (up to 5m). The average thickness of fill has been assumed to be 2.5 m across the site to take into account the areas with higher thicknesses of fill.

For the purposes of modelling a source area must be defined. The source area has been defined as the area of 500m x 500m as an initial model. Sensitivity analysis of this parameter is to be tested with smaller/larger source areas though this is relatively fixed as it is based on the proposed development platform.

Infiltration: The infiltration rate for the site is based on the local annual average rainfall for the area and the infiltration, based on that rainfall, modelled using the site conditions and vegetation. The typical average rainfall for Thorpe Marsh has been taken from the MET office. The closest MET office station is the Robin Hood Doncaster Sheffield Airport Station, which shows an annual average rainfall rate of 582mm/year, annual average 1991-2020[15]. The infiltration has been calculated based on the presence of grass/short vegetation and silty clay, considered representative of the site conditions, using the Thornthwaite potential evapotranspiration model. A resultant yearly recharge of 25mm/year is estimated from this model. This is noted to be approximately 4.25% of the annual rainfall.

Table 3-2 - Source Material Parameters

Parameter (Source)	Units	Base Model Value	Distribution	Justification
Source Width (parallel to groundwater flow)	m	500	Single	Development proposals
Source Length (perpendicular to groundwater flow)	m	500	Single	Development proposals
Thickness	m	2.5	Single	Development proposals, average thickness used
Moisture Content	%	9.8, 18.26, 33	Triangular	Site specific data
Particle Density	g/cm3	2, 2.65	Uniform	Site specific data

[15] Accessed 09/05/2024 https://www.metoffice.gov.uk/research/climate/maps-and-data/uk-climate-averages/gcx21p9fr

Parameter (Source)	Units	Base Model Value	Distribution	Justification
Dry Bulk Density	g/cm3	1.18, 1.37, 1.62	Triangular	Site specific data
Infiltration (effective recharge)	mm/year	25, 2.5	Normal	Based on MET office data and potential evapotranspiration calculations assuming vegetated surface

3.6 Pathway Characterisation

The modelled pathway is considered to be vertical leaching from the PFA source into shallow groundwater within the landfill and lateral migration of shallow groundwater off-site.

The fate and transport modelling requires parameters to describe the rate of leachability from the source materials and how this will move vertically through the unsaturated zone to groundwater.

The unsaturated zone must be characterised to define the partitioning characteristics of contaminants within unsaturated soils and infiltration rates required to determine the potential rate of leachate generation.

Model parameters are selected from site-specific field-derived data or, where site-specific data is unavailable, literature values have been used as a substitute (selected based on professional judgement). All unsaturated zone parameters are presented in Table 3.3 below. Base model values are provided as the final values selected for the modelling. Further consideration of these is provide in the Sensitivity Analysis in the following sections.

Table 3-3 - Unsaturated Zone Parameters

Parameter (Aquifer)	Units	Base Model Value	Distribution	Justification
Thickness	m	1, 2	Uniform	Site specific data
Dry Bulk Density	g/cm3	1.18, 1.37, 1.62	Triangular	Site specific data
Water Filled Porosity	fraction	0.25	Single	EA remedial targets worksheet porosity calculator using average site-specific moisture content, particle density and dry bulk density values.
Air Filled Porosity	fraction	0.154	Single	
Hydraulic Conductivity	m/s	2E-06, 6E-06, 1E-05	Triangular	Based on field permeability data.

The saturated zone must be characterised to define the pathway for contaminant movement within groundwater.

Table 3-4 - Saturated Zone Parameters

Parameter (Aquifer)	Units	Base Model Value	Distribution	Justification
Saturated Thickness	m	6,8	Uniform	Estimate based on local borehole records.
Hydraulic Conductivity	m/s	2E-06, 6E-06, 1E-05	Triangular	Based on field permeability data.
Hydraulic Gradient	fraction	0.005, 0.0058, 0.0066	Triangular	Based on site specific groundwater monitoring data.
Dry Bulk Density	g/cm3	1.18, 1.37, 1.62	Triangular	Site specific data
Effective Porosity	fraction	0.15, 0.3	Uniform	Estimate based on site geology
Saturated Pathway Length	m	50	Single	Assumed sensitive off-site receptor in close proximity to placement site
Longitudinal Dispersivity	m	5	Single	10% of pathway length (RTM calculated value)
Lateral Dispersivity	m	0.5	Single	1% of pathway length (RTM calculated value)

3.7 Receptor Characterisation

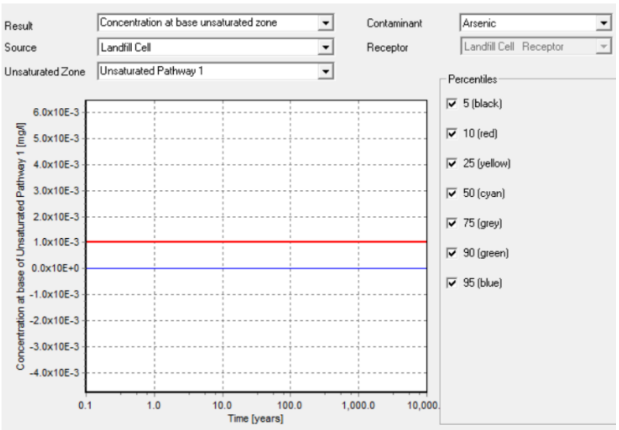
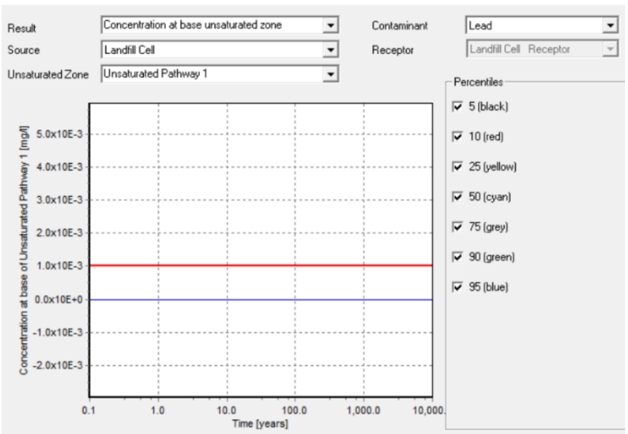
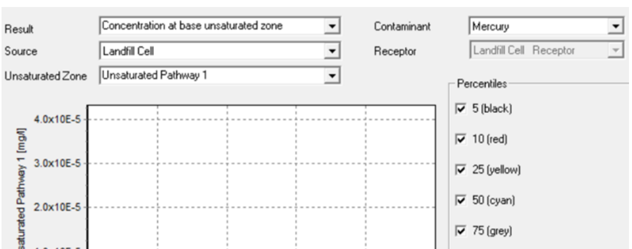
Compliance Point: Initial modelling at Tier 2 assumes the receptor is the groundwater below the site. WFD requirements states that for hazardous substances the compliance point must be the point at which leachate reaches the groundwater. Substances listed as non-hazardous to groundwater can be considered further to groundwater below the site and to an off-site receptor. In this scenario, an off-site compliance point has been set at a distance of 50m from the source area, this is also suitably protective of wider surface watercourses, although no clear pathway to wider drains has been identified in the CSM.

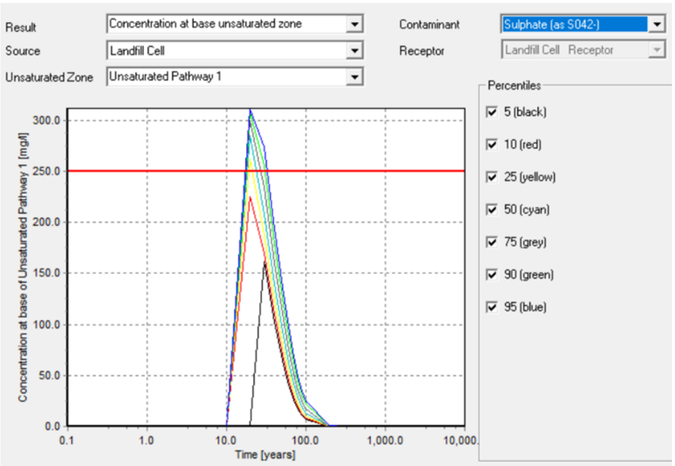
Compliance Criteria: The compliance criteria for hazardous substances are minimum reporting values to comply with the WFD requirement to prevent input of hazardous substances to groundwater. The compliance criteria for non-hazardous substances are defined to protect both potable water resource and the surface water environment thus, the lowest GAC are used for each compound to be protective of both receptors.

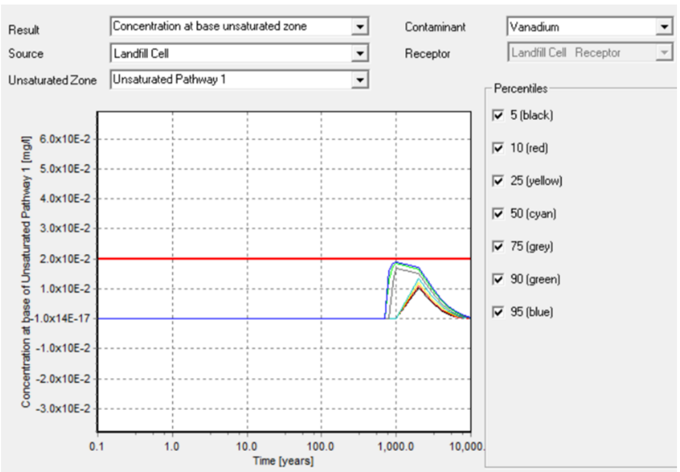
3.8 Base Model Outputs

Graphs showing the predicted concentrations at the base of the unsaturated zone over time are presented in Table 3.5 below along with discussion of significant features of the model for each compound. The horizontal red line in the graphs indicates the compliance criteria used for each compound,

Table 3-5 - Modelled Outputs at the Base of the Unsaturated Zone

Model Output	Discussion
Arsenic  	No predicted breakthrough within 10,000 years.
Lead  	No predicted breakthrough within 10,000 years.
Mercury  	No predicted breakthrough within 10,000 years.

<table>
<tr><th>Model Output</th><th>Discussion</th></tr>
<tr><td></td><td></td></tr>
<tr><td>Sulphate

</td><td>Predicted breakthrough >10 years.

The model indicates 50% probability that concentrations are predicted above the GAC at the base of the unsaturated zone before dilution.</td></tr>
<tr><td>Vanadium

</td><td>Predicted breakthrough >100s years.

Peak predicted concentrations are below GAC and therefore not of concern.</td></tr>
</table>

All hazardous and non-hazardous metals are predicted to be below the GAC/MRV at the base of the unsaturated zone and as such are no longer considered a risk.

Sulphate is a non-hazardous substance; however, is predicted to exceed the GAC at ~10-year time scale. Following dilution within the groundwater in the saturated zone, the maximum concentration of sulphate is predicted is ~200mg/l (GAC 250mg/l), as shown in Figure 3.1. This does not allow for any background concentration in groundwater. It has been shown from the groundwater sampling and analytical data that there are already elevated sulphate concentrations in the Drift groundwater body at concentrations greater than the GAC and greater than that recorded in the soil leachability analysis. The additional contribution from the new cell materials is considered minimal, with concentrations recorded similar to background concentrations in the sandstone aquifer.

Any further sulphate mobilisation from the new landfill cell materials is therefore considered insignificant in the context of the site and is not considered a risk to the water environment.

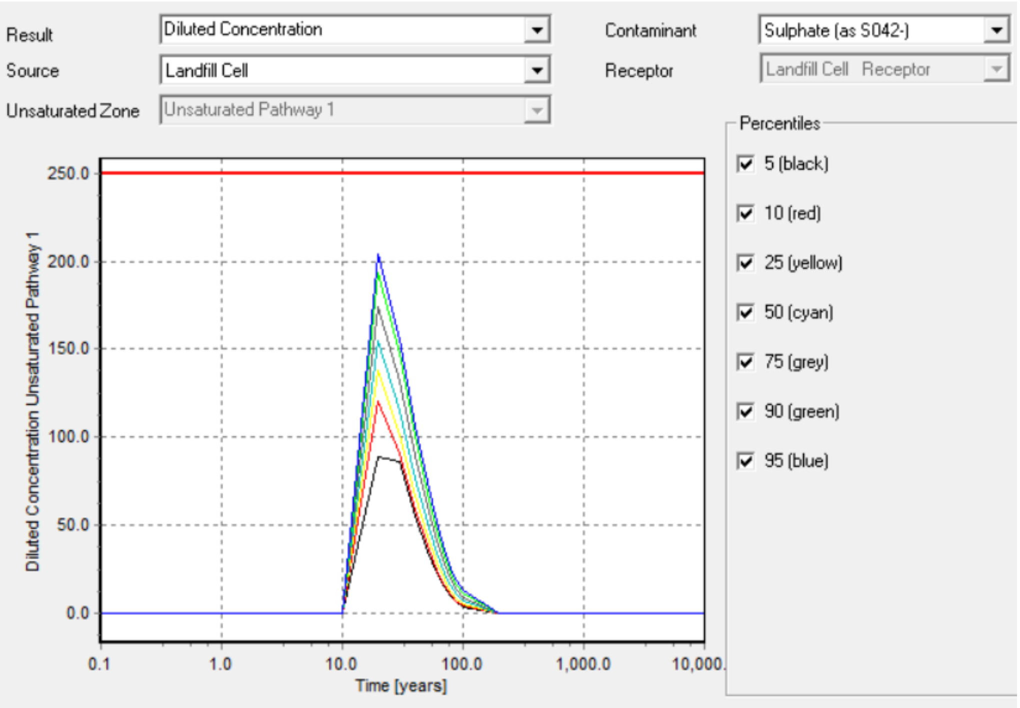


Figure 3-1 - Sulphate predicted concentration in groundwater beneath source.

3.9 Climate Change Considerations

The UK Government and devolved administrations have produced climate change adaptation programmes, including plans for both mitigating and adapting to climate change. SDGs support the development of Sustainable Cities and Communities (SDG No. 11), Clean Water and Sanitation (SDG No.6), sustainable ecosystems (SDG No.14. Life below Water and SDC No. 15 Life on Land). It is therefore important to recognise how changes in weather/season/climate could affect the ground conditions that were encountered during the investigation.

Climate change projections[16] demonstrate that in the UK the following conditions are expected to result from future climate change: drier and hotter summers, wetter and milder winters, a higher frequency of intense rainfall periods and sea level rise. The following are considered relevant to the assessment:

- **Increase in precipitation** – this may cause increased infiltration and a rise in groundwater levels leading to groundwater flooding, increased leaching, runoff and contaminant mobilisation and a potential change in locations of surface water receptors.
- **Drier, hotter weather** – this may increase potential for low permeability horizons to desiccate and permit a higher rate of infiltration, migration of contaminants from surface into subsurface, increase in groundwater abstractions causing change in flow paths or introducing new receptors.

The key parameters which require consideration under conditions of climate change are recharge, groundwater elevations (unsaturated and saturated zone thickness) and hydraulic gradient. As the effects of climate change in the UK are projected to be spatially variable it is necessary to seek an understanding of the changes in recharge and groundwater elevation as close as possible to the site being assessed.

[16] Meteorological Office UK (2018). UKCP18 Land Projections: Science Report. Updated March 2019.

The impacts of climate change have been considered within the modelling in the sensitivity analysis section below by incorporating the following:

1. Recharge, potential increase in rainfall and increase in recharge is considered by varying the infiltration rates from 25mm to 100mm effective recharge / year. This range is considered to be representative of the higher range of infiltration that may occur due to increased storms events/wetter weather as a consequence of climate change.
2. Change in groundwater elevations due to extreme weather events considered via variations in the unsaturated and saturated zone thicknesses.
3. Potential increase/decrease in hydraulic gradient due to variations in the groundwater elevations across the site.

3.10 Sensitivity analysis

There are numerous uncertainties in the modelling which are to a degree considered within the probabilistic modelling approach, however further sensitivity analysis for the modelling has been completed to better understand those parameters with low certainty and those parameters which may be altered by future climate changes.

The parameters defined in Tables 3.2 to 3.4 are considered again in Table 3.6 depicting sensitivity analysis on the impact of changing the parameter input on the model outputs.

Table 3-6 - Sensitivity Analysis

Parameter (Source)	Units	Base Model Value	Distribution	Sensitivity Analysis Input Ranges	Comment
Source Material					
Source Width (parallel to groundwater flow)	m	500	Single	Area of the fill is unlikely to change – understood that the fill will cover 26 Ha.	Not considered further.
Source Length (perpendicular to groundwater flow)	m	500	Single		
Thickness	m	2.5	Single	Range across site varies from 0 to 9.9m in thickness.	Moderately sensitive parameter. If the thickness of the source is increased to 9.9m the concentration of sulphate and vanadium at the base of the unsaturated zone increases with both CoC predicting an exceedance of the GAC at 95%ile concentration. The concentrations of these compounds predicted at the 50m receptor point are still below GAC.
Moisture Content	%	9.8, 18.26, 33	Triangular	Range based on site specific data.	Increases predicted concentrations reaching the base of the unsaturated zone slightly, however high confidence in range estimated and not change to conclusions of the HRA within reasonable parameter range.
Particle Density	g/cm3	2, 2.65	Uniform	Range based on site specific data.	High confidence in range estimate. Negligible difference noted varying the particle and dry bulk densities. Not considered further.
Dry Bulk Density	g/cm3	1.18, 1.37, 1.62	Triangular	Range based on site specific data.	
Infiltration (effective recharge)	mm/ year	25, 5	Normal	MET office data for the annual average rainfall for the site is noted to be 582mm/year with a yearly effective recharge of 25mm/year estimated from potential evapotranspiration models (assuming an open grassed site). A high estimate of 100mm, approximately 20% of the current average rainfall has been used to be indicative of increased infiltration from climate change induced events including increased rainfall and/or extreme heat events and surface desiccation.	Increased rainfall decreases the time period until breakthrough at the base of the unsaturated zone with mercury, sulphate and arsenic predicted to exceed the GAC/MRV, albeit still in a time period >1000s years for the hazardous metals. The value chosen for the base model is representative of the site in a compacted and covered scenario with the engineered surface water drainage system.

Parameter (Source)	Units	Base Model Value	Distribution	Sensitivity Analysis Input Ranges	Comment
				The estimate of 25mm/year is considered indicative of current infiltration. Infiltration will likely decrease post-development due to the proposed PFA compaction, har cover across parts of the site and the engineered drainage system.	
Unsaturated zone					
Thickness	m	1, 2	Uniform	Range based on site specific data	Limited effect. Range considered reasonable, based on site data and proposed development.
Dry Bulk Density	g/cm3	1.18, 1.37, 1.62	Triangular	Range based on site specific data	High confidence in range estimate. Negligible difference noted varying the dry bulk density. Not considered further.
Water Filled Porosity	fraction	0.25	Single	Based on EA remedial targets worksheet porosity calculator using average site-specific moisture content, particle density and dry bulk density values.	Limited effect. Range considered reasonable.
Air Filled Porosity	fraction	0.154	Single		
Hydraulic Conductivity	m/s	2E^{-06}, 6E^{-06}, 1E^{-05}	Triangular	Base model values are indicative of field tests. Lab trials recorded lower permeabilities in the order of 10^{-7}m/s. The proposed development will compact source materials to a permeability of approximately 10^{-7}m/s.	Reducing the hydraulic conductivity to 10^{-7}m/s increases the predicted length of time until contaminant breakthrough. Using the field trail data has provided a reasonable worst case estimate for the base model.
Saturated zone					
Saturated Thickness	m	6,8	Uniform	Estimate based on local borehole records	Limited likely mixing zone range and limited effect.
Hydraulic Conductivity	m/s	2E^{-06}, 6E^{-06}, 1E^{-05}	Triangular	Base model values are indicative of field tests. Lab trials recorded lower permeabilities in the order of 10^{-7}m/s.	Reducing the hydraulic conductivity to 10^{-7}m/s increases the predicted length of time until contaminant breakthrough.
Hydraulic Gradient	fraction	0.005, 0.0058, 0.0066	Triangular	Range based on site specific data	Limited effect. Range considered reasonable.
Dry Bulk Density	g/cm3	1.18, 1.37, 1.62	Triangular	Range based on site specific data	High confidence in range estimate. Not considered further.
Effective Porosity	fraction	0.15, 0.3	Uniform	Estimate based on site geology	Limited effect. Range considered reasonable.

Parameter (Source)	Units	Base Model Value	Distribution	Sensitivity Analysis Input Ranges	Comment
Saturated Pathway Length	m	50	Single	Assumed sensitive off-site receptor in close proximity to placement site	Off-site receptor not discussed
Longitudinal Dispersivity	m	5	Single	1% of pathway length (RTM calculated value)	Off-site receptor not discussed
Lateral Dispersivity	m	0.5	Single	1% of pathway length (RTM calculated value)	Off-site receptor not discussed

3.10.1 Sensitivity Analysis Discussion

3.10.1.1 Source materials

The source materials are well characterised by site specific testing undertaken on the PFA within the 2024 site investigation. It is understood that post-development the compacted PFA will act as a low permeability layer which will reduce potential infiltration and provide improvement compared to the current free draining situation (~10^{-5} m/s recorded in PFA groundwater monitoring wells) to a permeability in the order of 10^{-7} m/s. The impact of a reduction in infiltration rate on the model would be to increase the time to potential breakthrough of contaminants at the base of the unsaturated zone. As such, the parameters used in the base model are conservative and therefore protective of all scenarios.

3.10.1.2 Leaching and movement through the unsaturated zone

Infiltration rate estimates influence the predicted contaminant transport times and concentration in the groundwater. Higher infiltration results in shorter travel times before contaminant breakthrough. The infiltration rates used are considered to be more indicative of the likely worst-case infiltration on site post development taking into consideration the reduction in permeability of the source materials as discussed above, the increase in hard cover across the site and engineered surface water drainage system. Even allowing for climate change effects increasing this infiltration no significant impact is predicted.

The other unsaturated zone parameters effectively determine the rate of water movement down to the groundwater. Climate change may lead to variations in parameters such as the thickness of the unsaturated zone due to extreme weather events; however, variations in this are noted to have negligible impacts on the concentration of contaminants or breakthrough time at the base of the unsaturated zone.

3.10.1.3 Dilution and attenuation in the aquifer

The dilution in groundwater is calculated as a ratio between groundwater flow below the source and infiltration through the site. At lower infiltration rates a smaller volume of infiltrating water is present, although concentrations of contaminants may be slightly more elevated, when diluted in groundwater results in a higher dilution factor and therefore a much lower concentration in the aquifer than predicted with higher infiltration rates.

3.11 Quantitative Modelling Summary

Hazardous Substances (arsenic, mercury and lead) are not predicted to reach the base of the unsaturated zone in detectable quantities within a 10,000-year modelling time frame. This is due to the very low concentrations recorded in soil leachability tests and their low mobility in the environment. As such these compounds are not considered to be a significant risk to the water environment and require no further assessment or mitigation measures.

Vanadium, a non-hazardous metal, was predicted to breakthrough at the base of the unsaturated zone in ~100s years, however at concentrations below the GAC again indicating no significant risk to the water environment.

In contrast to the other CoCs, sulphate is significantly more mobile, as such it is predicted to breakthrough to the base of the unsaturated zone within a 10-year time frame, with the predicted concentrations likely to be above the GAC, peaking at around 310mg/l. This is noted to be only marginally higher than the GAC for 250mg/l.

Additionally, sulphate is measured in groundwater within the drift at a considerably higher concentration than recorded in the soil leachability analysis (1480mg/l average in Drift groundwater compared to 292mg/l average in the soil leachability analysis). Sulphate is also measured in the sandstone aquifer at concentrations averaging ~230mg/l. This suggests that over the decades of PFA placement, excess sulphate has already mobilised leaving what is now approximately equal to background aquifer concentrations.

There are numerous uncertainties in the modelling which are to a degree considered within the probabilistic modelling approach; however, to understand this further and to model potential climate change effects, a sensitivity analysis was completed.

The sensitivity analysis shows reasonable confidence in the input parameters with only minor differences in the predicted breakthrough time of contaminants at the base of the unsaturated zone. The parameters with the greatest variability and influence on the model were considered in detail and in respect of potential climate change effects and the proposed development of the site.

From this it can be concluded that there is no significant likelihood of hazardous substances and non-hazardous metals leaching at concentrations which would be measurable at the base of the unsaturated zone and thus there will be no discernible impact to groundwater from the new landfill cell materials. Sulphate may be detected at the base of the unsaturated zone but at concentrations like background concentrations in the sandstone aquifer and considerably lower than measured in the existing Drift groundwater on site.

4. Technical Precautions and Lifecycle Assessment

4.1 Lifecycle

The new cell is to be formed by relocation of PFA from the existing landfill and placement in compacted layers. This process may take a few years, and once the cell is complete, the landfill will be placed in to closure, and restoration undertaken.

No new material is to be placed and the material which will form the new cell has been characterised sufficiently to understand the full life cycle of the new cell in the modelling completed.

4.2 Leachate Management

Leachate which may be produced by the PFA in future is not considered to be contaminated based on the data available and modelling completed which demonstrates no significant risk to the water environment from the measured contaminant concentrations in the source material. No leachate management is required and therefore no leachate completion criteria are required.

The existing landfill was designed as a dilute and disperse landfill. The materials which will be moved to form the new cell have been demonstrated to have no significant concentrations of CoCs. This material has been open to infiltration for decades and no new material is to be placed at the site.

Leachable concentrations are lower than already found in the Drift groundwater and any leachate generated will result in a negligible contribution to contaminant loading to groundwater.

The proposed development of the site with managed drainage systems will also reduce infiltration which will in turn reduce the volume of leachate generated from materials in the new landfill cell and from the remainder of the landfill beneath.

4.3 Accidents and their consequences

There are no engineered systems incorporated into the risk assessment.

Given the simplicity of the proposals and that the earthworks are proposed to take place in one controlled phase of work Ramboll has not identified the potential for the constructed landfill cell to represent a significant risk to the environment from accident scenarios or unexpected events, particularly in the context that the PFA will not create new leachate or ground gas that may represent a secondary risk of pollution, fire, asphyxiation etc.

The site is located well above the predicted flood elevations for flood zone 2 and 3 in this area.

The stability of the proposed landfill cell and the construction of the BESS has been considered in the form of a stability risk assessment that is submitted with this application. This confirms the suitability of the proposed earthworks and the development will be subject to a detailed design process including consideration of project risks.

There is a residual potential for incidents to occur during any construction project from dust, noise, odours, release of fuels etc and as mentioned this will be managed through the project CEMP and detailed contractor method statements, furthermore, an environmental management system will be developed for the project.

The proposed landfill design considers the future redevelopment as a BESS and will include engineered surface water drainage management. This will need to be maintained over time and such maintenance will be inherently required given the nature of the proposed scheme as a grid connected BESS. The site has been assessed as an open site with sensitivity analysis identifying no significant risks even at higher infiltration rates. Therefore, any accident of failure of this system will not affect the hydrogeological risk assessment conclusions.

The surface water drainage system is further discussed in the Environmental Setting and Installation Design (ESID) report. Further details of the Planned Preventative Maintenance regime for the drainage system are provided in the ESID report. The drainage system has been designed such that rainfall within the new landfill cell is captured, stored in attenuation ponds and eventually discharged to the wider surface water drainage network. the landfill cell has been designed such that surface water run off that falls outside of the cell will not result in run-off back into the cell.

5. Conclusions and Recommendations

5.1 Conclusions

This report has been prepared to support the sustainable development of the Thorpe Marsh landfill where the intent is to relocate and re-use on-site PFA (~13% of the overall PFA present on-site) to create a new PFA landfill cell (which will ultimately form the development platform for the planned BESS) in accordance with the EA guidance including use of sustainability principles to re-use of low-grade materials in forming new landfill cells.

This HRA has considered the potential effects on the environment through the lifecycle of the proposed new landfill cell with the main focus being the long-term placement of PFA, and potential residual pollutant leaching, as part of the site's long-term redevelopment as the BESS.

Potential risks during the construction phase will be managed through use of a CEMP, detailed method statements and an Environmental Management System (EMS). There are a number of factors that limit the potential for residual leaching from the PFA to result in a significant impact namely:

- PFA has been deposited on the site prior to and in accordance with the existing WML and resulted in a general background of contamination on-site;
- Underlying groundwater is classed as unproductive strata due to the low permeability nature of the deposits with a Principal Aquifer located beneath, albeit with abstraction points >2km distant;
- The potential for substances to be released and infiltrate into the Principal Aquifer is limited as a result of the underlying significant thickness of low permeability superficial deposits, although towards the east of the site the rockhead is shallower and local hydraulic connectivity may be possible, which is acknowledged in this risk assessment;
- The CSM has not identified a direct groundwater pathway to nearby surface waters;
- Post PFA movement, surface water infiltration will be limited by the construction of a compacted low permeability PFA cell (with a permeability of 10-07m/s achievable) and an engineered surface water drainage system effectively preventing infiltration across the development area;
- On the basis of the above no leachate controls are proposed and PFA is considered to have no potential to generate significant quantities of landfill gas given the nature of the material;
- Contractors undertaking earthworks (landfilling) at the site will disturb the PFA and controls will be in place to mitigate against potential impacts;
- Laboratory leachate testing has identified only very low concentrations of CoCs and by the nature of the method used to generate the eluate, is considered to be an overly conservative method for assessing leachable potential. As an existing dilute and disperse landfill, leachable substances are expected to have largely already leached, as evidenced by the elevated concentrations in groundwater on-site and very low concentrations in soil leachability analysis;
- Arsenic, lead, sulphate and vanadium were the only compounds of concern identified in laboratory soil leachate results at concentrations above either the MRV (hazardous substances) or GAC (non-hazardous substances). Mercury was taken through the risk assessment with a worst-case assumption of concentrations potentially at the detection limit of the soil leachate analysis.

The outcome of the HRA modelling is discussed below:

- The HRA model for predicted concentrations at the base of the unsaturated zone over time did not identify concentrations of hazardous substances (arsenic and mercury) above the MRV over a period of 10,000 years.

- Predicted concentrations of vanadium (a non-hazardous substance) were modelled at the base of the unsaturated zone; however, these did not exceed the GAC and 'break though' was predicted at 100s of years, which is significantly longer than the proposed landfill aftercare period of 32 years.
- Although concentrations of sulphate (a non-hazardous substance) are predicted to exceed the GAC at ~10-year time scale, following dilution within the groundwater in the saturated zone, the maximum concentration of sulphate is predicted to be lower than the GAC. In addition, existing background conditions are significantly higher than the modelled concentrations and those from soil leachability analysis. Therefore, additional contribution from the new cell materials is considered minimal, with concentrations recorded similar to background concentrations in the sandstone aquifer.
- The HRA has identified that the PFA to be re-used to form the new cell has very low leaching potential with modelling demonstrating that even in a worst-case open (i.e., un-capped) setting with no engineered barriers the predicted concentrations at the base of the unsaturated zone are not significant. This includes the substances classed as hazardous, on the basis of the reported concentrations, the activity is not considered at risk of causing attributable, discernible concentrations of hazardous substances in the groundwater. Likewise for non-hazardous substances there is not considered to be a significant risk of the input of non-hazardous pollutants to groundwater.
- The proposed development will involve compaction of the PFA forming the new cell in layers to achieve a hydraulic conductivity of approximately 10^{-7} m/s, this will reduce permeability of deposits, leaching and migration potential.
- No engineered barriers (top and bottom liners) or leachate management systems are required. The proposed development design incorporates drainage systems to take surface water runoff which will reduce infiltration and potential leaching from the new cell and the remainder of the landfill beneath. The development is therefore anticipated to reduce risks to groundwater long term from the entire WML (landfill) site not just the 13% of the PFA to be moved for the new landfill cell.
- The proposed landfill design takes into account the site's long-term use as a BESS, therefore the risk profile would not change or increase as a result and given the proposed construction methods.
- Consideration has been given to effects that may arise because of accidental or unexpected events, however, given the limited leaching potential of the PFA, the proposed design and nature of the operations, no significant effects have been identified.
- Potential climate change effects have been considered in the modelling and are negligible. The proposed design measures will manage and reduce infiltration and are expected to result in lower groundwater levels in the PFA. Surface water run-off will be managed and designed to take account of potential future climate change effects.

Overall, the proposed permit variation works including movement of existing PFA to create a new PFA landfill cell (and ultimately a BESS development platform) will regenerate and reduce the risk profile of the existing closed landfill including managing surface water run off more appropriately and leading to biodiversity improvements.

It can therefore be concluded that the proposed permit variation will meet the relevant standards of the Environmental Permitting Regulations 2016[17] and further it can be concluded that the proposed landfill design will not only prevent unacceptable discharges and emissions over the entire lifecycle of the new landfill cell including aftercare, but will reduce the emissions from the remainder of the dilute and disperse landfill, providing betterment to the wider landfill site as a whole.

[17] https://www.legislation.gov.uk/uksi/2016/1154/contents/made

5.2 Proposed Monitoring and Completion Criteria

The HRA has demonstrated that the leaching potential of the PFA to form the new cell is very low and no leachate management, or leachate completion criteria are required.

Groundwater in the Drift deposits is already impacted from the dilute and disperse landfill (described in more detail in the CSM report). Impacts include compounds not detected at significant concentrations in the leachate from the new cell. The new cell is not predicted to add a significant contaminant loading to the groundwater in the Drift. The new development is likely to reduce infiltration and therefore leaching potential for the landfill as a whole. Groundwater levels beneath the new landfill cell may also fall to some degree as the recharge mound effect currently seen in the landfill is likely to reduce with the reduced infiltration due to the proposed new landfill cell and BESS development design and surface drainage management systems. This will also reduce the rate of leaching from the remainder of the landfill material beneath the new cell.

A groundwater and surface water monitoring plan are provided in the Monitoring Plan and summarised in the ESID to continue to monitor trends in the groundwater levels and CoC concentrations during and after construction.

Appendix 1
Figures

Appendix 2
Stirling Maynard Drawings

Appendix 3
Screened Dataset

Appendix 4
Combined Dataset