Nuclear Waste Services

MONITORING

2026 Environmental Safety Case for the LLWR

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Preface

The Low Level Waste Repository (LLWR) is the United Kingdom's principal facility for the disposal of solid Low Level Waste (LLW). It is a near-surface disposal facility in which waste was disposed in trenches and is now being disposed in vaults excavated into the ground surface. The LLWR is owned by the Nuclear Decommissioning Authority (NDA) and operated on their behalf by a wholly-owned subsidiary division, Nuclear Waste Services Ltd.

We, Nuclear Waste Services, are committed to operating the LLWR as a safe and efficient facility that provides a continuing option for the disposal of LLW in the United Kingdom. This will be achieved consistent with good practice for the near-surface disposal of radioactive waste, in accordance with environmental, health and safety, and security regulation and guidance, and in compliance with the terms of our Nuclear Site Licence and Permit to dispose of radioactive waste. We are also committed to working with the NDA to ensure optimal use is made of the LLWR to support the NDA's mission, in accordance with government policy. This may involve the disposal of a broader range of wastes than just LLW as currently defined in the United Kingdom[1].

One of the means we use to operate the LLWR safely is to maintain and implement an Environmental Safety Case for the site. This is one of the reports presenting the 2026 Environmental Safety Case for the LLWR – the 2026 ESC. The 2026 ESC is a major update based on a comprehensive review of our previous 2011 ESC and subsequent developments. The 2026 ESC addresses both the environmental safety of the disposal facility and the rest of the site. It considers the disposal of both LLW and some less-hazardous Intermediate Level Waste (ILW). Assessing the disposal of some less-hazardous ILW does not imply any decision has been made to dispose of such waste at the LLWR. The work has been undertaken to understand the safety implications if such a decision were made and hence support consideration of the option by the NDA.

The 2026 ESC is issued under the authority of the Nuclear Waste Services' Executive Director of Sites and Operations.

The 2026 ESC consists of documents at two levels:

- A single 'Level 1' report outlines the plan for the development of the LLWR and the main arguments concerning environmental safety and how it is achieved.
- A series of 'Level 2' reports present the evidence that underpins our safety arguments, including descriptions of our management framework, system understanding, design and management choices, assessments and implementation.

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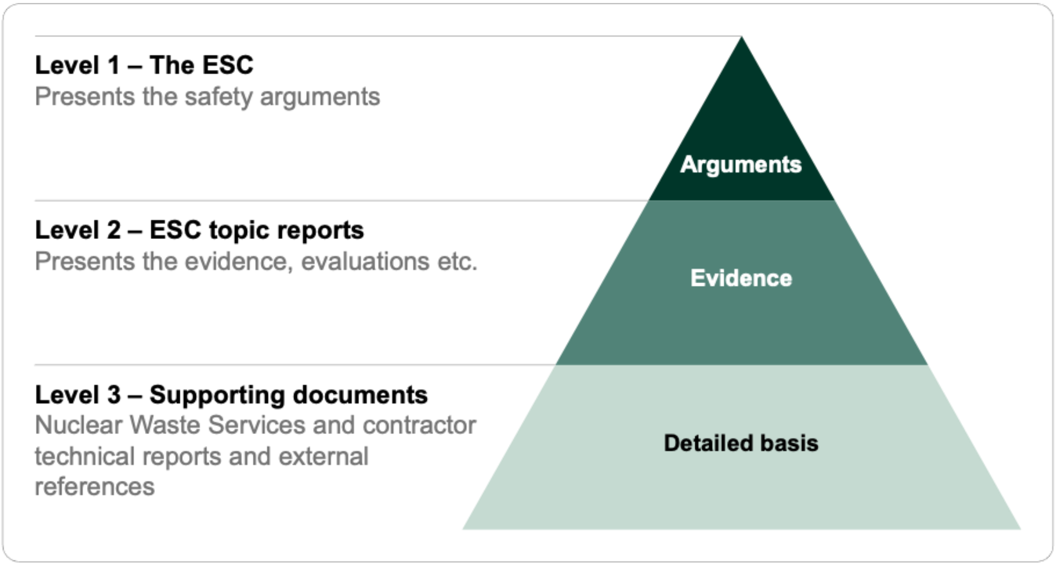
[1] In government policy, LLW is defined as radioactive waste having a radioactive content not exceeding four gigabecquerels per tonne (GBq t^{-1}) of alpha or 12 GBq t^{-1} of beta/gamma activity.

This is the Level 2 report ‘*Monitoring*’. The ESC Level 1 and 2 reports are listed in the table below, which also shows for the Level 2 reports the set of arguments for which each report mainly provides evidence. A brief description of the contents of each Level 2 report is also given. The ESC is supported by a large number of technical and scientific reports and references that we refer to as ‘Level 3’ documents. We have also produced a Guide to Key Points of the ESC, to help a wider group of stakeholders understand its nature, conclusions and implications.



Level 1	
Main Report [1]	
Level 2	
Management and dialogue	
Management and Dialogue [2]	Describes our environmental management systems and interactions with regulators and stakeholders
System characterisation and understanding	
Site History and Description [3]	Provides a history and description of the site
Disposal Facility Inventory [4]	Describes the wastes already disposed and wastes that may be disposed at the facility
Engineering Design [5]	Presents the engineering design of the current facility and proposed changes as further disposal vaults are built and the disposal facility is closed

Near Field [6]	Describes our understanding of the chemical and physical evolution of the engineered disposal system
Hydrogeology [7]	Describes our understanding of the geology and hydrogeology of the site
Site Evolution [8]	Describes our understanding of how the site will evolve, with a focus on coastal erosion
Monitoring (this report)	Presents our programme of environmental monitoring supporting the ESC
Optimisation and Site Development Plan	
Optimisation and Site Development Plan [9]	Describes our approach to optimising the design and management of the disposal facility and wider site, and sets out our Site Development Plan
Waste Management Plan [10]	Presents our plans for managing the wastes produced by previous uses and operation of the site
Assessments	
Safety Functions [11]	Presents our understanding of how the different aspects of the repository system and its management contribute to the safety of the facility
Engineering Performance Assessment [12]	Presents our analysis of how the various components of the engineered disposal system will perform, which is an input into our impact assessments
Environmental Safety During the Period of Authorisation [13]	Presents evidence that the LLWR is currently being operated safely and will continue to be so during the period that the facility is permitted
Assessment of Long-term Radiological Impacts [14]	Presents evidence that, if the LLWR is managed in accordance with the Site Development Plan, the site will remain safe in the long term
Hydrogeological Risk Assessment [15]	Presents evidence that the disposal facility protects groundwater from both radiological and non-radiological contaminants in the disposed wastes now and will continue to do so in the future

Assessment of Radiological Impacts on Non-human Biota [16]	Presents evidence that the LLWR does not have adverse consequences for non-human biota populations now and will not in the future
Implementation	
Implementation [17]	Sets out how we use the ESC to manage the site, including setting Waste Acceptance Criteria and other controls on the types and quantities of waste accepted for disposal
Audit	
Addressing Regulatory Requirements and Feedback [18]	Provides a cross-reference between the contents of the ESC and regulatory guidance and feedback

Executive Summary

Regulatory guidance on the authorisation of near-surface disposal facilities for radioactive waste requires that the developer/operator of the facility should carry out a programme to monitor for changes caused by construction, operation and closure of the facility. This requirement applies during the period in which the site holds an environmental permit. This time period is referred to as the Period of Authorisation. The regulatory guidance also describes the need for a reasoned and proportionate approach to the design of the environmental monitoring programme. This document describes how the requirement is currently delivered, along with the strategy behind the environmental monitoring programme, its current status and proposed future development.

The environmental monitoring programme at the LLWR forms an integral component of the overall environmental safety case (ESC) for the facility. This includes monitoring of groundwater, surface water, leachate, and gas composition. The aim is to assess the impact of the site on the surrounding environment and ensure compliance with environmental standards. This report explains how the monitoring programme has been designed and implemented to provide a sound underpinning to the safety arguments presented as part of the 2026 ESC.

Environmental monitoring provides a fundamental basis for understanding the site and its evolution over time. It provides feedback on the performance of the various barriers to the release of contamination and informs the process of optimising the facility. An appropriate environmental monitoring programme, applying sound science and best practice, is vital to building confidence in successive safety assessments. Similarly, the results of successive safety assessments are used to inform the design of the monitoring programme. The programme not only meets statutory requirements but also adheres to best practice guidelines, ensuring that the methodology is both robust and appropriate. It is a 'live' monitoring programme that can be adapted in response to site developments, to investigate anomalous results or incorporate the latest scientific and technical advancements. It is managed through a systematic approach, involving regular reviews and updates to ensure that it remains proportionate.

Environmental monitoring data are available from the late 1980s through to the present. This allows the longer-term trends to be identified and the effectiveness of engineered barriers assessed. The results indicate that the LLWR site has minimal impact on the environment and risks to the general public are negligible. The results also provide a baseline against which changes due to future operations can be assessed.

Environmental monitoring data are used systematically within the ESC and are particularly important in providing inputs to, and calibration data for, the 3-D groundwater flow model of the site, near-field evolution, site evolution and as a basis for comparison with assessment model results.

As the site operator, we, Nuclear Waste Services, recognise the need for a programme of long-term environmental monitoring that will continue throughout the Period of Authorisation. The monitoring programme has been modified in recent years to adapt to the capping programme. The programme will continue to require changes as new vaults are built and the site moves from operational to a fully capped and closed repository. The data collected will contribute to future updates of the ESC, which is expected to build confidence in our understanding of system performance and support permit surrender in the future.

During the Period of Authorisation, environmental monitoring will provide assurance that the facility is performing as expected. Monitoring data will provide a direct demonstration that the relevant criteria are being met and that the concentrations of any contaminants in environmental media are acceptably low.

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1 Introduction

1.1 Objectives

This report addresses Requirement 14 (see box) of the environment agencies' Guidance on Requirements for Authorisation (GRA) [19], which sets out the need for an environmental monitoring programme in support of an Environmental Safety Case (ESC).

> **Requirement R14: Monitoring**
>
> In support of the environmental safety case, the developer/operator of a disposal facility for solid radioactive waste should carry out a programme to monitor for changes caused by construction, operation and closure of the facility.

The GRA also describes the need for a reasoned and proportionate approach to the design of the environmental monitoring programme. This report also contributes to addressing the environment agencies' Guidance on Requirements for Release (GRR) Requirement R8: Site characterisation and monitoring [20] in providing information needed to support the development of a Waste Management Plan (WMP) and Site Wide Environmental Safety Case (SWESC). These and other details of the regulatory guidance are discussed in more detail in Section 3.

The monitoring programme is designed to meet the needs of a range of end users, including the ESC. This document explains how the needs of the ESC are being addressed. It describes the strategy behind the Low Level Waste Repository (LLWR) environmental monitoring programme, its current status and proposed future development. An outline of monitoring programme results is provided to illustrate key findings and to indicate how data have been used within the ESC.

The environmental monitoring programme at the LLWR forms an integral component of the overall ESC for the facility. This report explains how the monitoring programme has been designed and implemented to provide a sound underpinning to the safety arguments presented as part of the 2026 ESC. Furthermore, the ongoing accumulation of monitoring data will progressively improve the baseline against which the future performance of the LLWR can be compared.

In this report, we set out how the LLWR's monitoring programme is:

- designed to meet the regulatory and other requirements;
- the outcome of an appropriate methodology;
- managed in an appropriate way;
- used to support the current ESC and how it is expected to change throughout the Period of Authorisation (PoA).

1.2 Scope

The LLWR environmental monitoring programme is designed to monitor the performance of the site and to assess its potential impact on the surrounding environment. It comprises a comprehensive programme of environmental measurements on, or adjacent to, the LLWR. The programme involves the analysis of samples, management of data and the use of monitoring data to improve understanding of the site and its performance.

This report provides background on the development of the monitoring programme, details of the current monitoring programme, how the results are assessed and how they have been used to support the ESC. The report also covers how the programme is expected to develop during the lifetime of the site and how long-term monitoring will be used to understand the performance of the engineered barriers and provide confidence in the performance of the disposal system. The role of the monitoring programme to inform contaminated land decisions and support site developments is also presented and supports the *'Waste Management Plan*' (WMP) [10]. The report does not address predisposal monitoring or characterisation of the wastes that will be disposed to the LLWR as requirements for this are addressed in the ‘*Implementation*’ report [17].

The environmental monitoring data, results and conclusions in this report are closely linked to those presented in some other ESC reports. Examples are as follows.

- The ‘*Near Field*’ report [6] incorporates arguments and conclusions that are underpinned by the environmental monitoring programme.
- Groundwater monitoring provides a baseline for understanding the hydrogeological system and its evolution (described in more detail in the ‘*Hydrogeology*’ report [7]). Monitoring data have been used as a basis for the testing and calibration of groundwater flow models.
- Models presented in the ‘*Site Evolution*’ report [8] are underpinned by coastal monitoring data collected as part of this programme.
- Assessments of the radiological and non-radiological impacts of the LLWR during the PoA are based in part on monitoring data. Models used to estimate impacts at later times have also been based in part on monitoring data. During the PoA, monitoring together with possible remediation to address any deterioration in performance, will provide assurance of appropriate levels of safety. This is discussed in the ‘*Environmental Safety during the Period of Authorisation*’ report [13]. The radiological assessment models calculate radionuclide concentrations in environmental media as an intermediate output. These concentrations are used as input to the ERICA Tool [21] to evaluate their radiological impacts on non-human biota. This is discussed in the ‘*Assessment of Impacts on Non-human Biota*’ report [16]

Overall, monitoring contributes to the conceptual understanding of the system providing understanding of the sources, pathways and potential receptors used in the assessment of the safety of the site.

1.3 Structure

In this report:

- Section 2 provides a brief summary of the site (in part informed by the results from the monitoring programme) for general background information. Key aspects of the geology, hydrogeology and engineered features are described and links are made to more comprehensive information.
- Section 3 sets out the objectives and scope of the monitoring programme. It describes how the monitoring programme has been designed to meet the requirements of the GRA and other statutory obligations. The interactions between the operator and the regulators in defining the monitoring programme are outlined. It sets out this programme in the context of regulatory requirements and the needs of a range of projects, including the ESC. The Quality Management processes that ensure the acquisition, handling, processing, record keeping and management of the data conforms to current best practice are also described.
- Section 4 describes the main features of the current monitoring programme. This section also summarises some of the key results of the monitoring programme since the 2011 ESC and how these results have been interpreted to understand specific aspects of the site.
- Section 5 summarises some of the key results of the monitoring programme since the 2011 ESC and how these results have been interpreted to understand specific aspects of the site.
- Section 6 describes how the monitoring data and modelling approaches have been used in a complementary way to build confidence in site and system understanding
- Section 7 sets out the approach to long-term monitoring and expected future developments, and Section 8 provides conclusions.

2 Understanding the LLWR Site and Facility

2.1 Site Setting and History

The LLWR is located on the coastal plain of West Cumbria near the village of Drigg and approximately 0.5 km from the Irish Sea coast at Drigg Beach. It is approximately 3 km north of the Ravenglass Estuary where the Rivers Irt, Mite and Esk converge. The Rivers Irt and Mite flow roughly south-west from the inland Lakeland fells. The River Esk is separated from the other rivers by the prominent ridge of Muncaster Fell.

The site occupies an area of approximately 100 ha, of which approximately 40 ha form the existing waste disposal area, see Figure 2.1. The topography surrounding the site varies from 25 m above Ordnance Datum (m OD) to the north-east, and at Barn Scar Hill to the west of the site, to less than 5 m OD at the south-eastern site boundary. To the west of the site, the topography gently undulates towards a small cliff line marking the edge of the Drigg Beach. Inland of the LLWR the topography rises, initially gradually but then steeply, to be dominated by the Lakeland fells.

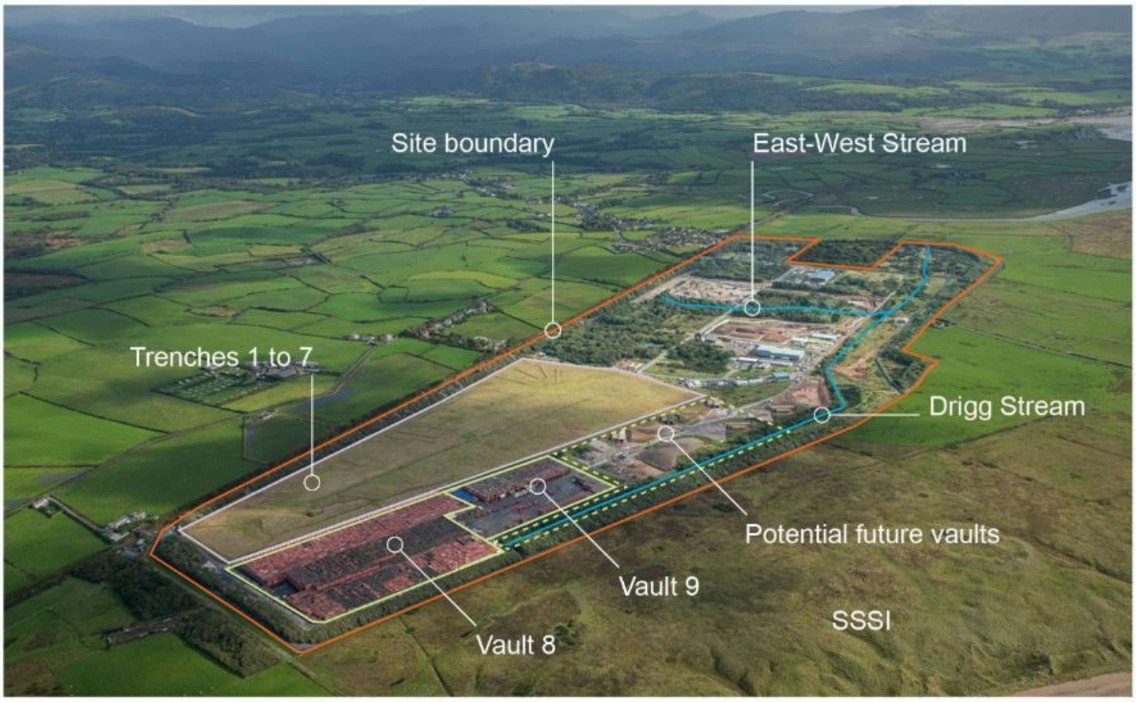


Figure 2.1: Key features of the LLWR

The broader coastline is characterised by a beach and inter-tidal zone with sand dunes and low cliffs inland. Most of the coastal plain consists of grassy fields with only a small amount of land dedicated to woodland and the growing of crops. Roads and minor tracks allow access to the coastal plain and to settlements that are located there.

Currently, the closest point of the LLWR vaults lies approximately 350 m inland from the present-day coastline and studies [8] have indicated that the site may be disrupted by coastal erosion or inundated as a result of sea-level rise in the future. The most likely outcome is considered to be disruption of the LLWR site by undercutting of the engineered structures within a timeframe of several hundreds to a few thousand years. The '*Site Evolution*' report [8] provides details of the expected evolution of the site and the underpinning studies that have been conducted.

A railway line runs along the entire length of the north-eastern boundary of the site. Along the western boundary, the site borders a Site of Special Scientific Interest (SSSI). The site is principally surrounded by grazing land. Photographic and map evidence from the early 1940s suggests that the principal use of the area, prior to the site being used as a Royal Ordinance Factory (ROF) was for agriculture. More detail is provided in our *'Site History and Description*' report [3].

Manufacture of the explosive trinitrotoluene (TNT) began at the site in 1941 and continued until 1945 [22]. Subsequent to the conclusion of the World War II, the site was also used as an area for munitions decommissioning. Historical practices during operation and demolition of the ROF facilities have also resulted in areas of ground contamination (of asbestos, TNT and lead).

The site has been in operation as a Low Level Waste (LLW) disposal facility since 1959. Wastes were originally disposed by loose tipping into a series of trenches (1 to 7). Disposals of containerised waste to Vault 8 commenced in 1988, with disposals to Trench 7 ceasing in 1995. Vault 9 was fully constructed in 2010. The trenches have been capped with an interim cap, constructed in 1988 and extended in 1995, to limit infiltration of rainwater and prevent intrusion into the waste. A cut-off wall was constructed along the northern end of the trenches and along the eastern side of Trench 6 in 1988 and extended along the eastern side of Trench 7 in 1995. Replacement of the interim membrane over the southern part of the trenches commenced in 2025. This will be followed by construction of the final cap over Vault 8 and the northern part of the trenches as illustrated by Figure 2.2. Details of the engineering are provided in our '*Engineering Design*' report [5].

A former Cumbria County Council landfill site is located adjacent to the south-eastern site boundary, although it did form part of the ROF site. It was originally used for domestic waste disposal between 1966 and 1974, operated by Millom Rural District Council. However, given its age, the exact nature of the materials disposed of is not known and may have included contaminating substances. From 1974 onwards, it switched to inert waste only (e.g., highway maintenance material). Cumbria County Council granted planning permission for continued operation in May 2004, but the site is now closed and monitored under an Environment Agency permit.

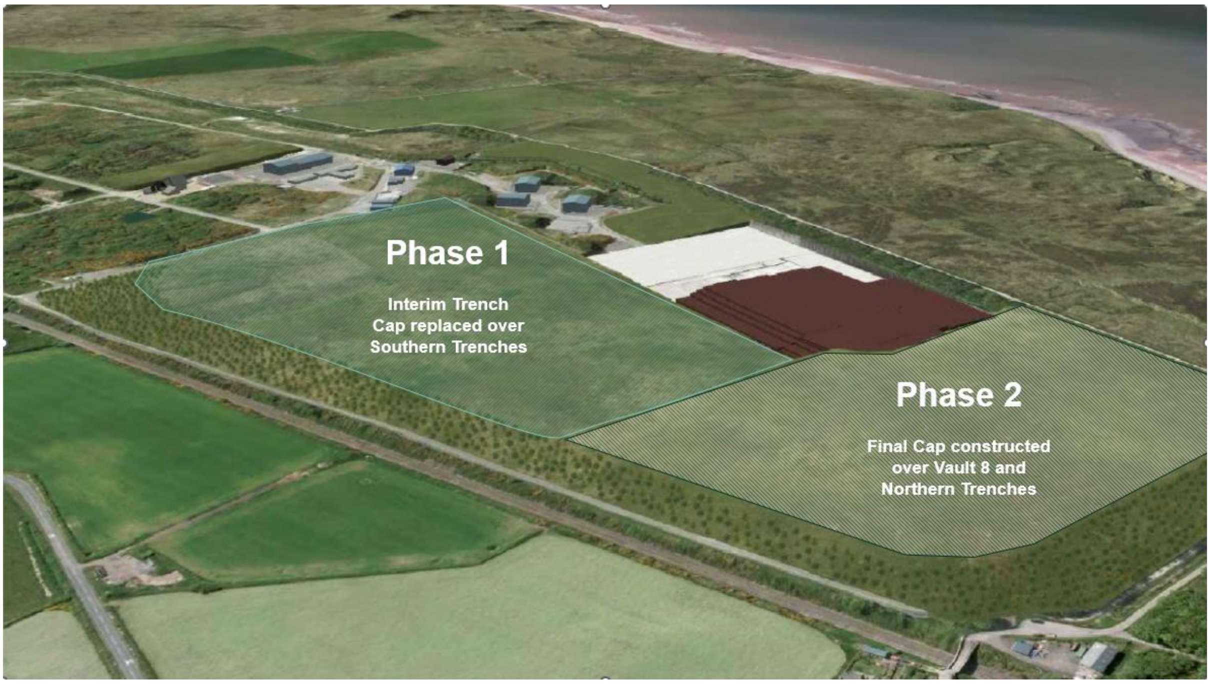


Figure 2.2: Phase 1 and 2 of capping.

Construction of additional vaults is planned, potentially up to Vault 12 based on current inventory projections [9] although designs extend to Vault 14 to retain flexibility, with waste emplacement ceasing in 2135. Once the vaults are filled, a multilayer final cap will be placed over the trenches and vaults. It is anticipated that this will be done progressively with cap construction occurring over the same period as construction of additional vaults. The final cap will include a region of profiling fill, a gas collection layer, a low permeability geomembrane, a gravel drainage layer, a bio-intrusion barrier consisting of large cobbles, a low permeability clay layer, a filter layer comprising sand and coarse gravel and subsoil and topsoil cover.

The highly engineered final cap is designed to:

- restrict water infiltration and encourage run-off;
- isolate and protect the waste from intrusion and erosion;
- control release of gases;
- resist damage due to movement and settlement;
- resist damage due to erosion and intrusion by plants, animals and humans;
- have a low visual impact to the surrounding area; and
- perform passively without maintenance after the PoA.

The cut-off wall will also be extended around the disposal area as the cap is progressively installed. After site closure, the site will remain under active institutional control for around 100 years, during which monitoring and remedial actions remain possible [13].

2.2 Geology

The LLWR site and its surrounding area have been the subject of extensive surface and sub-surface investigation for decades (particularly since the 1990s). The sub-surface in the region consists of thick (up to 70m) Quaternary age (last 2.6 million years) deposits overlying bedrock. The Quaternary deposits are particularly important for the hydrogeology because the LLWR is a near-surface facility. A detailed review of the geology of the area and the development of the geological conceptual model is provided in our '*Hydrogeology*' report [7]. Recent investigations have contributed substantially to the current geological understanding of the formation of bedrock and Quaternary deposits in the region. A new geological conceptual model of the Quaternary deposits has been derived using an integrated stratigraphic methodology, applying multiple approaches, including an event stratigraphy and lithostratigraphy [23]. This allows better understanding of the geological complexity, processes and the connectivity of different units in areas where there are little data.

Made ground occurs across the majority of the LLWR as a result of site development. The thickness of the made ground is variable across the site and may, in some locations, be over 2.5 m. Made ground typically comprises a mixture of sand and clay with some gravel, representing reworked natural materials originating from within the LLWR, with occasional construction waste such as brick and concrete fragments.

2.3 Hydrogeology

The '*Hydrogeology*' report [7] provides a detailed review of the work done since the 2011 ESC in the developing the hydrogeological understanding. This includes the update of the hydrogeological conceptual model [24], to include recent developments in the geological model [23]. However, these developments have not changed the basic understanding of the groundwater flow. In the vicinity of the LLWR, groundwater generally flows sub-horizontally from the Lakeland fells towards the coast. Groundwater flow occurs within the Quaternary drift deposits and in the underlying Ormskirk Sandstone. Figure 2.3 shows a schematic representation of the hydrogeological conceptual model.

The Regional Groundwater occurs within the deeper Quaternary deposits and the underlying bedrock. It is distinguished from the Upper Groundwater by differences in the characteristics of the groundwater head. In the Regional Groundwater, there is not a significant vertical head gradient in the measured heads. Instead, there is a weak horizontal gradient that is generally perpendicular to the coastline. Flow is roughly from north-east to south-west, driven by the weak horizontal gradient. In areas where the upper part of the bedrock is sandstone, flow in the upper part of the bedrock makes a significant contribution to the regional groundwater flow.

Although the data suggest that it is possible to distinguish between the Upper Groundwater and the Regional Groundwater, they are not separate systems. Groundwater flows between them.

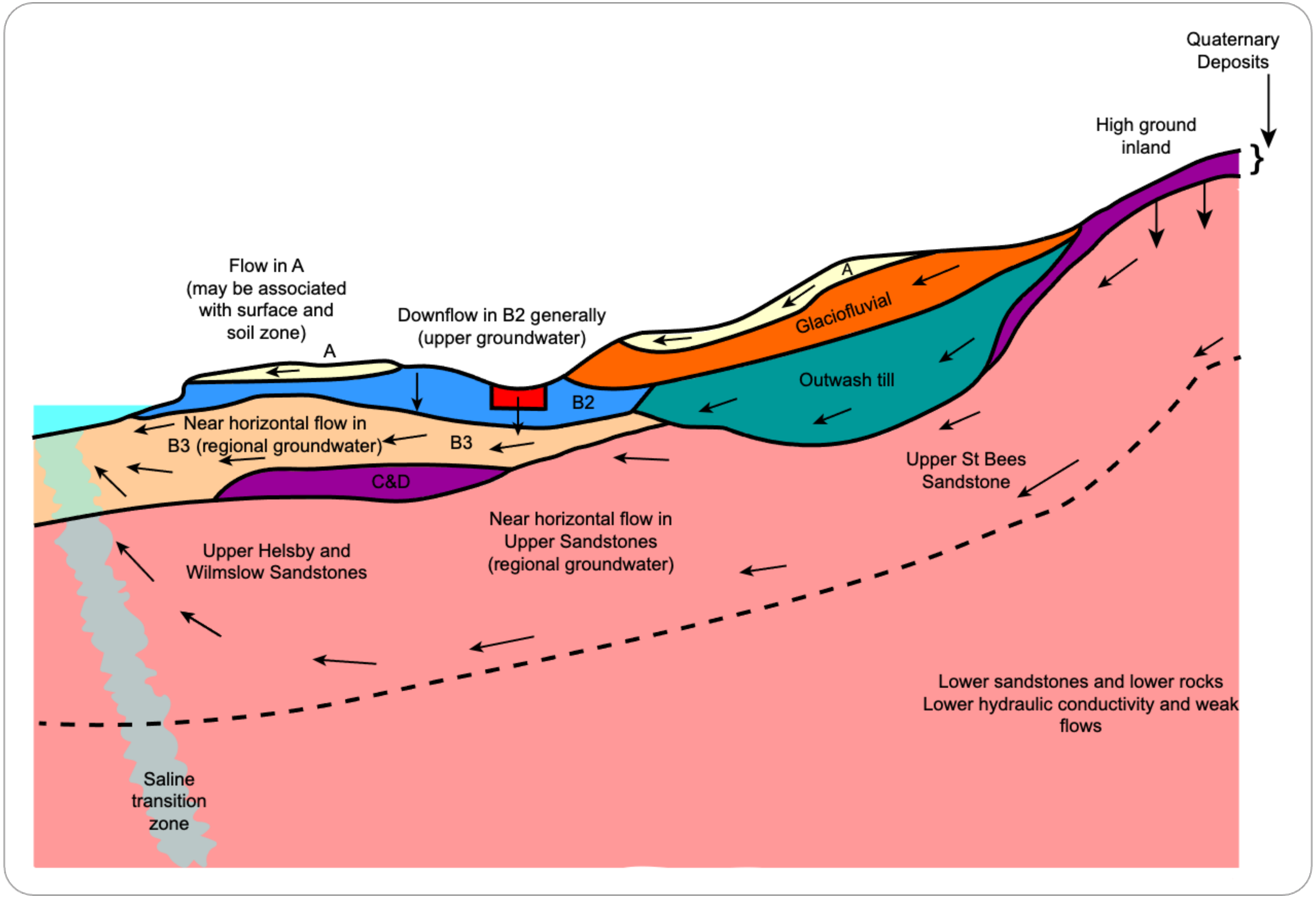


Figure 2.3: Hydrogeological conceptual model [24]

The flow is generally downwards in the Upper Groundwater, although, in places, the flow has a significant horizontal component. In discharge areas, which onshore are generally near streams, the flow has an upwards component. The flow in the Regional Groundwater is roughly horizontal, ultimately discharging into the sea.

There are localised discharges from the groundwater to the streams near the LLWR: the Drigg Stream and the East-West Stream. A component of the Regional Groundwater passing under the south-eastern part of the site discharges to the River Irt and the Ravenglass Estuary. Several engineered structures – including the northern section of the Drigg Stream, a railway line and associated drain (running in a cutting along the north-eastern site boundary), trench and vault engineering and a historical surface and sub-surface drainage system – all affect groundwater flow to a greater or lesser extent.

Measurements of the groundwater head in the vicinity of the site, and in monitoring wells with response zones at varying levels in the geological sequence, have allowed identification of the groundwater systems present at different depths. Based on the screen location the groundwater monitoring data is subdivided into the following categories:

- Upper Groundwater: is present within the upper Quaternary deposits (B2 in Figure 2.3) and overlies the Regional Groundwater. It is most evident in the north-west and central parts of the site, where it has a groundwater flow pattern that is distinct from that of the underlying Regional Groundwater, being predominantly downward, with very little lateral flow. Groundwater monitoring wells with screen bottoms above 6 m OD in shallow superficial deposits are considered to lie in the Upper Groundwater.
- Regional Groundwater: is observed in the basal Quaternary drift deposits (primarily in B3 in Figure 2.3) and within the underlying Ormskirk Sandstone. The groundwater flow direction in the Regional Groundwater at the LLWR is generally to the south-west. Groundwater from this zone discharges to the inter-tidal zone and further offshore. To allow further delineation of groundwater chemistry, the Regional Groundwater is split into two further subcategories, as follows:
    - Medium Groundwater: monitoring wells with screen tops between 6 m OD and above 10 m OD, which are screened in deep superficial deposits and the upper sandstone, are considered to lie in the Medium Groundwater.
    - Deep Groundwater: monitoring wells with screen tops below 10 m OD, which are screened in the sandstone aquifer, are considered to lie in the Deep Groundwater.
- Intermediate Groundwater: is not considered to be a distinct groundwater system but covers monitoring wells with screen depths crossing the Upper and Regional Groundwater boundary.

Towards the south-eastern boundary of the site, the direction of groundwater flow in the Upper Groundwater system merges with that in the Regional Groundwater system and, therefore, the two systems cannot be differentiated in this area.

Figure 2.4 shows the average values of the heads measured in boreholes around the LLWR plotted against the average elevation of the screen interval in the borehole used to make each measurement. Above about 4 m OD, the heads show a strong linear correlation with elevation, rising with increasing elevation with a gradient of about 1, However, for lower average screen elevations, the groundwater heads show significant variability, but are not correlated with elevation.

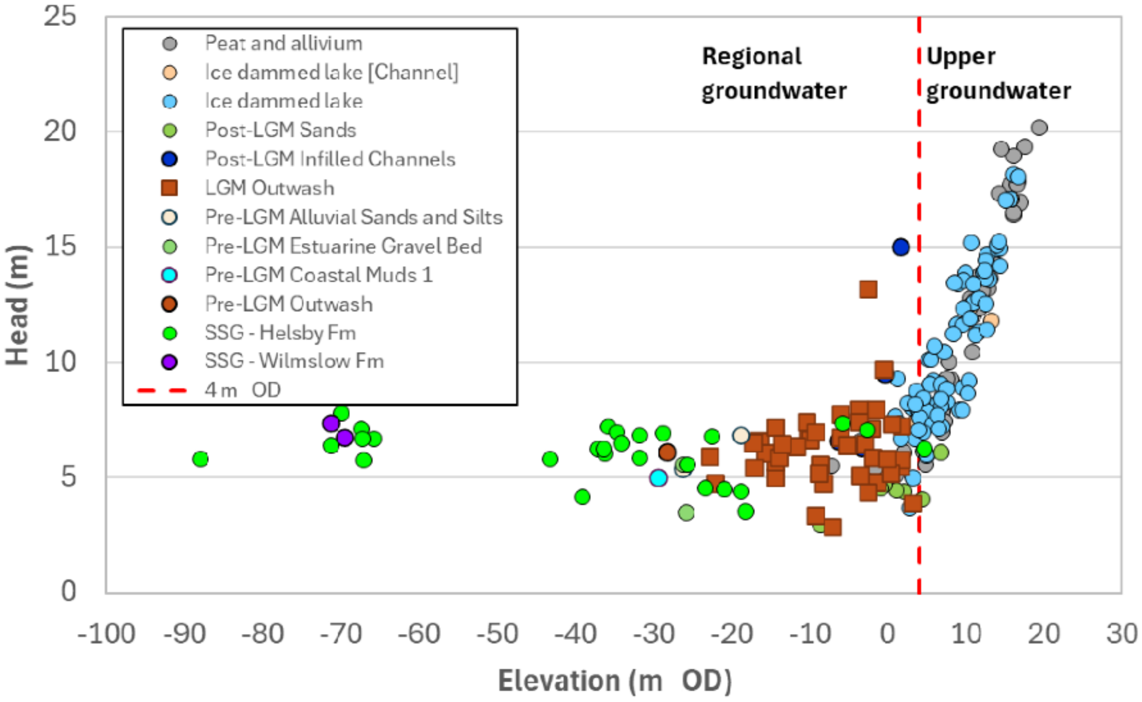


Figure 2.4: **The observed heads in the boreholes near the LLWR plotted against the elevation of the centre of the screened interval. The figure also shows the 4 m OD elevation, which is the approximate boundary between the regional and Upper Groundwaters. The points are coloured according to the units for the geological model [24]**

This suggests that there are two zones, with different characteristics, within the groundwater below the surface and soils zone. There is an Upper Groundwater (above about 4 m OD) in which it is expected that groundwater flow will be dominantly vertical, and a Regional Groundwater in which there may be local upwards or downwards vertical flows, but overall flow will be nearly horizontal, and will therefore form part of the regional flow. It is noted that transient head measurements in the Upper Groundwater show a faster response to rainfall than those in the Regional Groundwater. The bases of the trenches (12 to 15 m OD) and vaults (15 to 16 m OD) are all constructed above the Regional groundwater.

In Figure 2.4, the heads are coloured according to the geological units they are associated with. The 4 m OD level is roughly coincident with the base of the Ice Dammed Lake units. This suggests that the distinction between the Upper and Regional groundwater zones (near the LLWR) could be associated with the change in lithology from the Ice Dammed Lake units to lower units (Proximal Outwash and the sandstones).

The Ice Dammed Lake units consist of a sequence of alternate clay, and sand and gravel layers. The clay layers are laterally extensive around the LLWR and have relatively low hydraulic conductivity. This will lead to a relatively low effective vertical hydraulic conductivity of an Ice Dammed Lake unit (considered as a single unit). Therefore, significant recharge will lead to high vertical head gradients within the Ice Dammed Lake units. In contrast, the LGM outwash unit mainly consists of sands and gravels, which would be expected to have high hydraulic conductivity. Therefore, the vertical head gradients are relatively low within this unit.

Figure 2.5 shows that the head in the Regional Groundwater generally follows a trend with a decrease from inland towards the coast. The head gradient decreases significantly at distances greater than about 1 km from the coast, as indicated by the trend line. The trend seen in these two figures suggests that, generally, the flow in the Regional Groundwater will be from the high ground inland towards the coast. Transient head measurements in the Regional Groundwater show a level of tidal variations, which suggests a hydraulic connection between the Regional Groundwater and the sea.

In Figure 2.5, there are some anomalous regions of higher heads marked as 'outliers'. These are seen on the south-west boundary of the LLWR as well as on the northern boundary. The outliers on the south-west boundary have previously been referred to as the 'groundwater mound' and were discussed in detail in the 2011 ESC [25], but additional data suggest there is more complexity than one single mound area, which is understandable, noting the complexity of the Quaternary deposits in the region. The ‘outliers’ are mostly associated with permeable Quaternary deposits that are currently considered to be part of the Pre-Scottish Readvance Outwash and the LGM Outwash, although two of the seven relate to the lower permeability Post-LGM Infilled Channel deposit. Figure 2.6 shows a contour plot of the groundwater heads with the outliers removed.

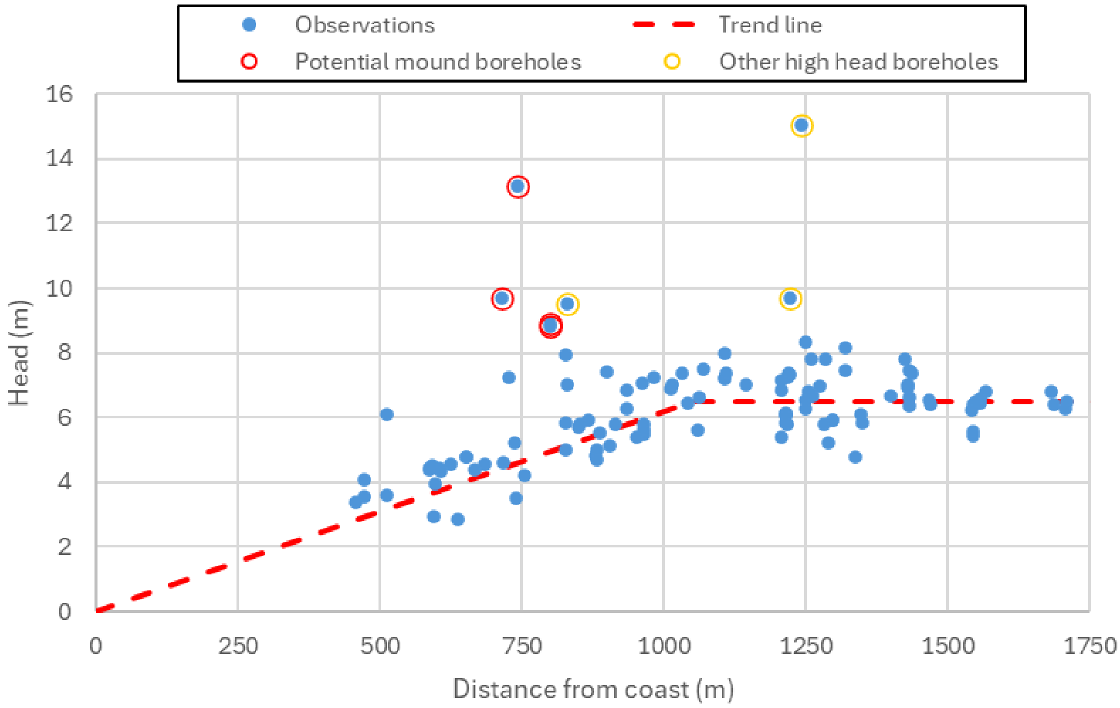


Figure 2.5: The heads in the Regional Groundwater plotted against the distance from the coast. Outliers from the general trend potentially associated with the groundwater mound, are circled [14].

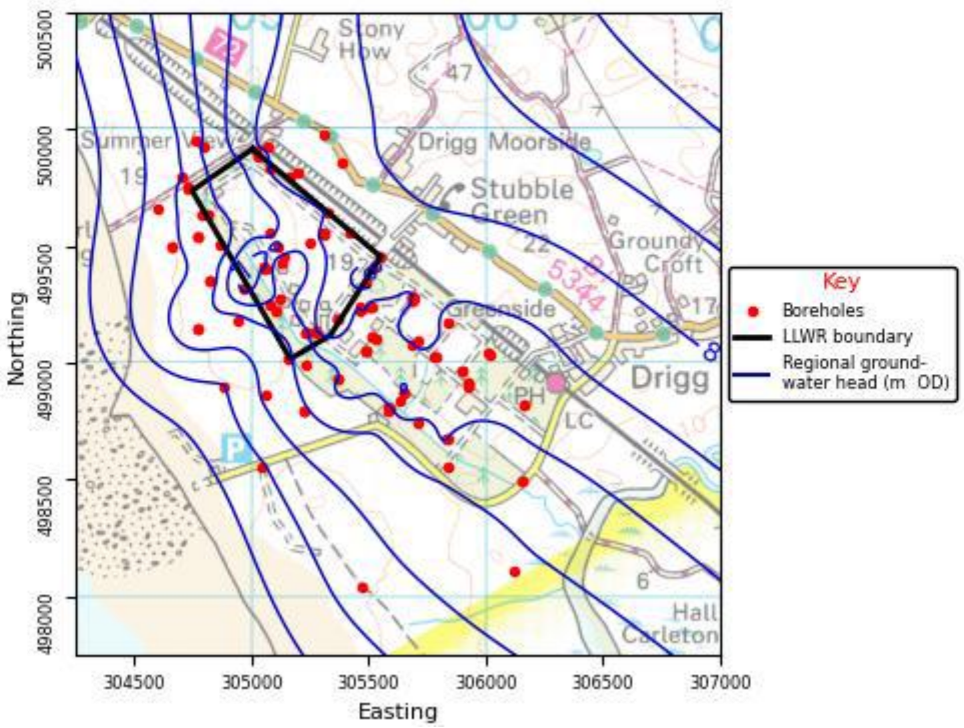


Figure 2.6: Interpolated contours of the groundwater heads in the Regional Groundwater around the LLWR site (with outliers removed). The contours are at 1 m intervals [14].

The LLWR site is located in a small surface water catchment area, see Figure 2.7. The catchment is drained by the Drigg Stream, which rises immediately to the south of Vault 8, and the East-West Stream, which rises to the north-east of the site in farmland and is a tributary to the Drigg Stream on the site.

Across the LLWR site, these streams are fed by numerous drains, for example, the railway drain, which is located parallel to the north-eastern edge of the trenches. The Drigg Stream discharges into the tidal section of the River Irt. The River Irt is located about 500 m to the south-east of the south-eastern boundary of the LLWR site and flows to the south-east for about 2.5 km before entering the Ravenglass Estuary. This estuary includes the confluence of the Irt, Mite and Esk Rivers. The confluence with the Drigg Stream is about 500 m downstream of the railway viaduct across the River Irt. Waters within the Ravenglass Estuary interact with the Irish Sea. There are a series of ponds on the SSSI to the west of the site. The water levels in these pools has been monitored to determine whether they are a potential receptor. Combined with the groundwater level data from adjacent boreholes the pools have been confirmed as being predominantly ephemeral and not groundwater-fed [26]. As such they are not considered to be a potential receptor.

As part of the cap construction work, a new Sustainable Urban Drainage System, including multiple lagoons to aid sediment removal, has been installed across the site to support surface water management relating to this work. The details of these arrangements are included in our '*Engineering Design*' report [5].

Any water that has come into contact with disposed or stored waste is considered to be leachate. Leachate from the end of each trench and from the vaults is and pumped into the leachate collection system, which drains to the Marine Holding Tank (MHT).

The trenches have a downward slope from the north to the south to promote drainage of leachate into the leachate collection system. The leachate in the trenches is, however, at a similar elevation to the surrounding Upper Groundwater and it is believed that they are hydraulically connected. Any leachate that is in contact with the Upper Groundwater will preferentially migrate vertically into the underlying Regional Groundwater. The majority of leachate is collected via the leachate collection system. Authorised leachate discharges were to the Drigg Stream prior to 1991 and afterwards to the Irish Sea via the MHT and Marine Pipeline.

A water features survey carried out in 2023 [27], combined with information on private water supplies in the area was provided by Cumberland Council [28], indicates that there were no private water supplies and licensed abstractions in the vicinity of the site, as shown in Figure 2.8, and that the site does not lie within a source protection zone. NWS has recently been granted a water abstraction licence [NW/074/0007/012] to allow the use of one of the on-site boreholes to supply water for dust suppression as part of cap construction works.

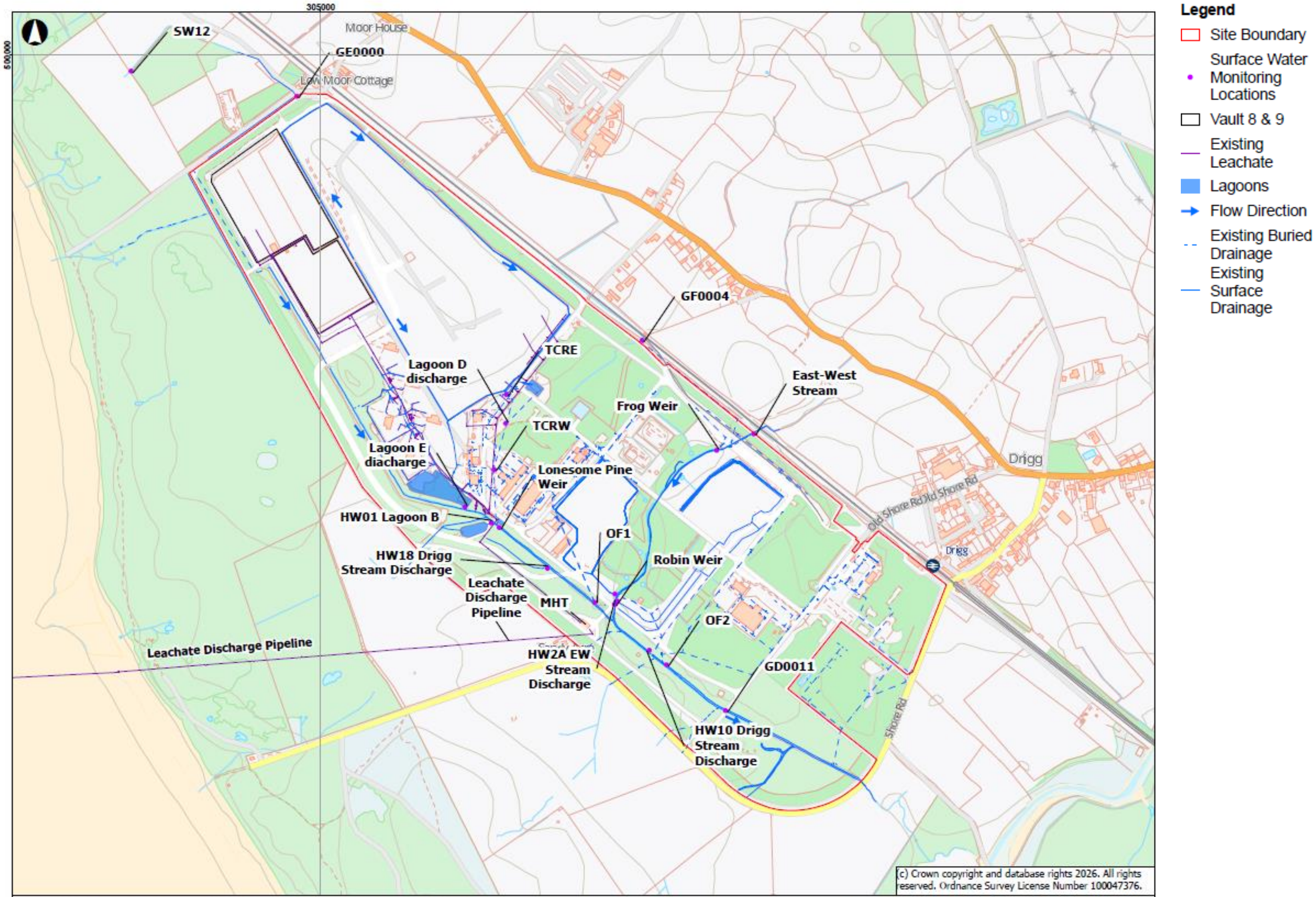


Figure 2.7: Streams, surface water drains and leachate drains near the LLWR

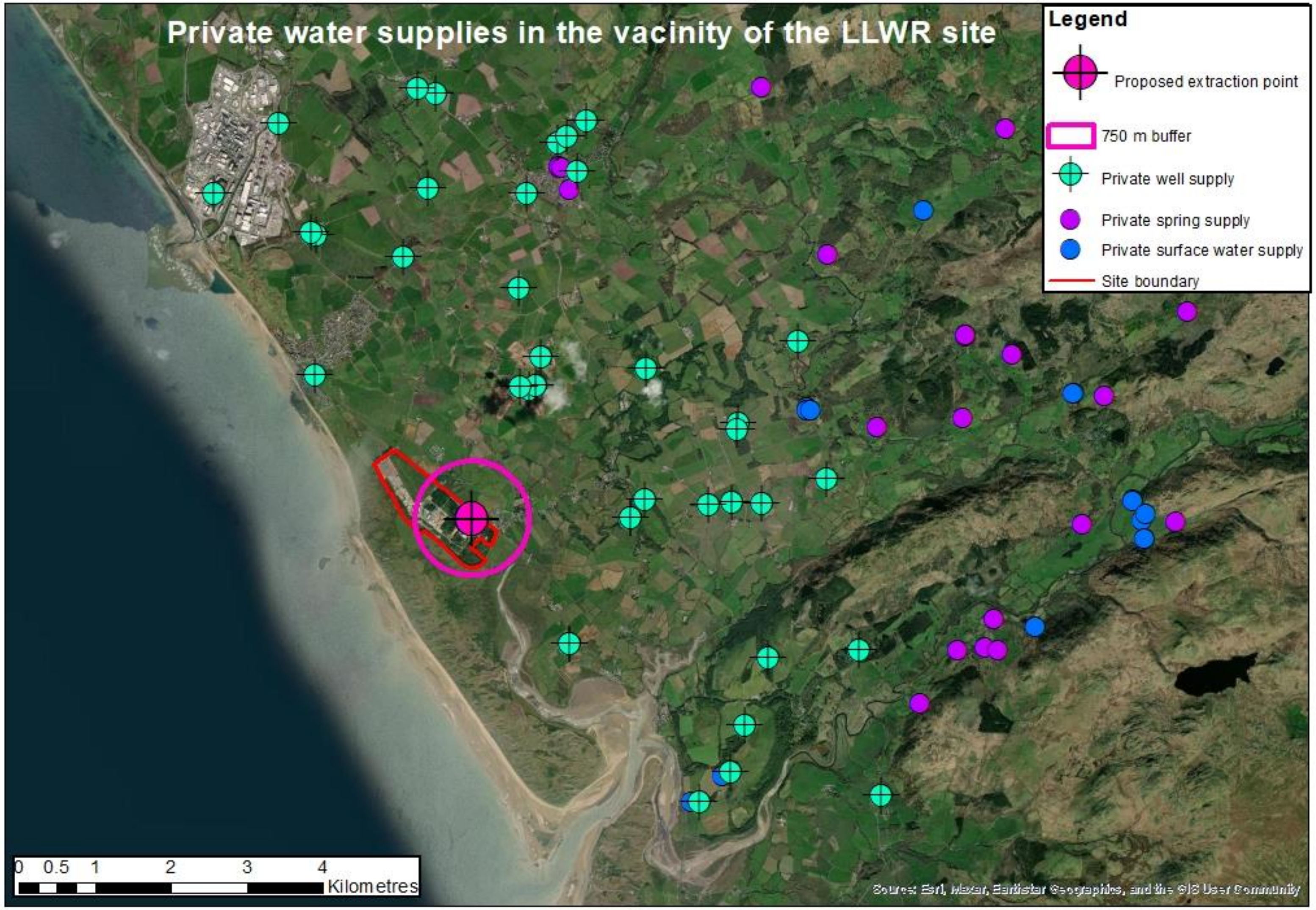


Figure 2.8: Private water supplies in the vicinity of the LLWR site

LLWR groundwater is dominated by meteoric input, modified by ion-exchange processes and by equilibrium with calcite in some locations in the Regional and Deeper Groundwater Systems [29]. Some limited mixing with deeper water is not ruled out.

The redox conditions can be characterised as moderately reducing, with evidence for denitrification but not for sulphate reduction. The redox conditions are consistent with or slightly less reducing than predicted for control by iron minerals, iron oxyhydroxides and siderite, which are known to be present as minor phases or coatings in the LLWR sediments. There is significant uncertainty in the redox potential associated with the LLWR groundwater, reflecting variability that may include two distinct redox environments.

2.4 Potential Sources of Contamination

The assessments of the potential future impact to receptors from contaminant sources are based on conceptual models of the LLWR site and facility. The potential sources and pathways identified for the LLWR facility are outlined in this subsection. The pathways relevant to monitoring are broadly related to releases to the air, surface waters, groundwaters and via direct radiation. Descriptions of the relevant exposed groups and receptors during the PoA are provided in the '*Environmental Safety during the Period of Authorisation*' report [13].

The land contamination at the LLWR comprises both radiological and non-radiological contamination from several sources. In many areas a certain type of contamination is dominant, however, radiological and non-radiological contamination often coexist. Information on the contaminated land investigations and potential sources is recorded in the Site Characterisation Report [30] .

For the purposes of this report, land contamination is defined as the below-surface accumulation of radioactive and non-radioactive contaminants, excluding authorised disposals within their designated disposal areas. Land contamination may have resulted from the following.

- Legacy from the ROF operations and buildings. Operations on the site involved the storage of raw materials (toluene, sulphur, coal, paraffin, lead, asbestos etc), production of mixing of chemicals (nitric acid, sulphuric acid etc) and ultimately the production and storage of TNT. Predominantly in the southern part of site.
- Ground contamination due to storage of plutonium contaminated material (PCM) in the magazines (south of Vault 9).
- Contaminant migration from authorised LLW disposal areas (Trenches 1 to 7 and Vaults 8 and 9).
- Migration of contaminants from off-site such as from agricultural run-off.
- Migration of contaminants from the former municipal landfill.

- Radiologically contaminated concrete slabs (B749, the ROF accommodation building slab adjacent to site entrance, and B741, a former ROF bunded area adjacent to Drigg Grouting Facility) from historic operations.
- Contamination arising from other site operations (vehicle maintenance, equipment cleaning etc).
- Leakage from the LLWR leachate management system.
- Road and rail (fuel spillage, oil leaks etc).

LLW disposal operations and the associated leachate from the vaults and trenches are licensed for disposal and contained within a managed system, and therefore are not considered to be contaminated land. The agreed end state [31] for the site is for ecological/recreational use and that appropriate assessment criteria would be applied to determine whether remediation is required. At present, remediation is undertaken as required to support site development controlled by the Site Development Plan [9].

In 2015, a land contamination risk assessment was produced [32] including the development of a conceptual site model and Tier 1 risk assessment. Following completion of the risk assessments, the conceptual site model was updated to include areas of concern by highlighting the principal sources of contamination on-site and delineating the likely extent of contamination using the collected data. The areas of concern identified have subsequently been subject to a series of investigations allowing the land contamination risk assessment to be updated [30]. We have recently produced a Land Quality Register that sits within our management system as the principal method of recording our latest understanding of contaminated land. It will be maintained as a live database, hosting the information relevant to each area of concern. The current version documents a total of 32 areas of concern, which are overlaid on the map of the site in Figure 2.9.The areas of concern chart the source, type, location and extent of contamination across the site based on our conceptual understanding of the site's historical use and existing site characterisation information, in addition to an interpretation of the level of risk that the contamination presents, in terms of risk criteria that are dictated by the site's interim and final end state. They are expected to change over time in response to the collection of more data or if the areas are remediated. This information has been used to inform monitoring requirements.

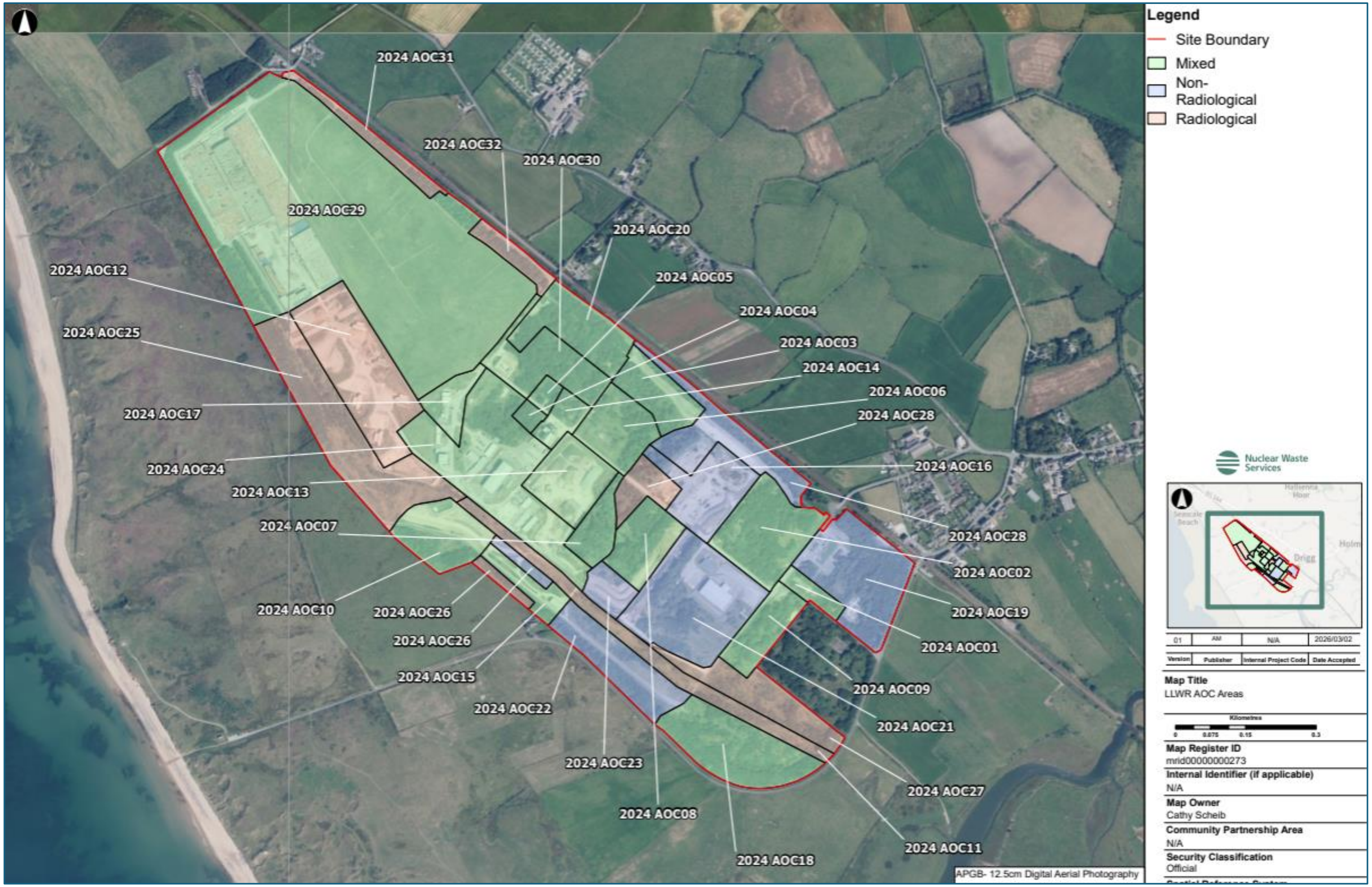


Figure 2.9: LLWR Site with Areas of Concern (AOCs) for Radiological, Non-Radiological and Mixed contamination

2.4.1 Site Operations for the Royal Ordnance Factory

Work to construct the ROF for the manufacture of TNT commenced in 1939 and manufacturing began at the site in 1941. Operations on the site involved the storage of raw materials, mixing of chemicals and ultimately the production and storage of TNT. Production of TNT continued, with an average weekly output of over 400 tonnes, until August 1945. Waste TNT was subsequently burnt on site.

Although definitive process information is not available, it is thought that trinitration of toluene occurred in a three-stage process [33]. Nitric acid and oleum were used to add progressively more nitro (NO_2) groups to the initial toluene ring. Toluene was nitrated to mononitrotoluene (MNT), MNT was then nitrated to dinitrotoluene (DNT) and then DNT was nitrated further to TNT. After completion, remaining acids and other impurities were washed out using alkaline sulphites or carbonates for reuse or disposal and the pure TNT piped to drying, flaking and packing facilities prior to storage at the magazines.

The acids required to produce TNT were either mixed on site or imported from other areas of the country. Part of the on-site chemical processing included the recycling of spent acid. Several of the plants on site were specifically designed for this purpose.

Prior to being washed and combined with soda ash to neutralise the pH, the TNT produced from the trinitration plants was acidic. The acidic TNT was run by gravity in lead-lined heated troughs in overhead gantries (situated about 6 m above the ground). Anecdotal evidence suggests that the acid content of the TNT corroded the lead-lined troughs and they were prone to leakage and needed frequent replacement.

The MNT production buildings were located in an area adjacent to the main acid production and storage area. They comprised buildings for the nitration, separation and storage of the MNT.

Toluene was delivered to the site by rail and stored in large, earth bunded tanks to the south-west of the site. Paraffin was also stored in tanks at this location. When required, toluene was pumped via a pipeline to the main production area.

Each of the TNT processing plants was surrounded by an earth bund. The bund was constructed to a height above the building roof as a precaution against explosion.

Ten earth-bunded magazines, located in the north-western part of the site, were used to store the finished TNT. The magazines were linked to the main areas of the site by an access road and a series of railway sidings.

It is assumed that the TNT waste store and burning hearth were used for burning waste explosive materials. These plants were located about 200 m north-west of the main TNT manufacturing facilities.

ROF plans indicate that the surface water drainage system fed directly into the two surface water streams on site. In addition, the following engineered drainage systems were constructed:

- Process Effluent Drainage System: the system collected waste process effluent that was essentially acidic, along with wastewater, and diverted it into the marine outfall pipe. The pipe then passed off-site to the west and discharged into the Irish Sea at the low water mark.
- Non-process Drainage Systems: One system collected foul water from buildings and diverted it into an outfall drain that passed off-site to the south-east, through a sewage treatment plant, and ultimately discharging to the River Irt. The second system collected surface water only from roads, buildings and other facilities. It then discharged to the south-west into the Drigg Stream.

Railway lines were present across much of the site and provided a link to the main railway line. The railway line also linked the main process and storage areas on site.

The area in the north-west of the site, currently occupied by Vault 8, previously comprised four storage areas, two coal dumps and two coke dumps. A stores compound was also located in this area.

A vehicle decontamination area was located immediately to the east of the oleum plants, north of the current DGF, and comprised two open pit soakaways that were used to discharge the washings from railway stock and road vehicles to ground. Plans of the building also record that it contained a bleach store.

2.4.2 Vault and Trench Disposals

The LLW disposals at the LLWR form the main potential source of contamination at the site. They consist of a wide range of materials, such as paper, cardboard, plastic, cloth, soil, rubble and metal. The wastes in the trenches and the vaults have the potential to generate leachate and run-off containing both radiological and non-radiological contaminants. There is also the potential for landfill gases and radioactive gases to be produced from wastes in both the trenches and the vaults. Further details of the trench and vault disposal are given in the '*Disposal Facility Inventory*' report [4].

Sediment is trapped in collection chambers at the end of each trench and is also allowed to settle in the MHT prior to discharge. Flow from the vaults is higher than from the trenches due to rainfall collection, but contaminant levels measured in waters draining the vaults are low.

Residual radioactivity is present in the Drigg Stream as a result of leachate discharges prior to 1991. The radioactivity is bound to sediments in the stream bed, leading to small, declining concentrations of radioactivity in the stream water as the radionuclides slowly desorb. Radionuclides in stream sediment can also be transferred to adjacent soils through occasional flooding and other processes. Recorded concentrations of radionuclides are low [34]. Provision is included in the Environmental Permit (the Permit) to allow for diversion of Vault 8 and Vault 9 drainage to the Drigg Stream in the event of extreme rainfall. The last confirmed use of the diverter valve was prior to the lifting of discharge restrictions in 1996.

The historical presence of elevated tritium levels in the railway drain indicates the presence of a pathway from the trenches to the railway drain. In order to try to minimise the migration of contaminants from the LLWR, an interim cap was constructed over the trenches and a bentonite-cement slurry cut-off wall was constructed initially around the north-eastern and north-western edges of trenches between September 1988 and August 1989. Current and historical monitoring data from the railway drain show that tritium levels have significantly reduced in the years following the installation of the cap and cut-off wall to the extent that there is no longer a pathway between the trenches and the railway drain.

2.4.3 Other Sources

Immediately adjacent to the LLWR on the southern boundary, is a closed inert landfill site, previously operated by Cumbria County Council, that is not expected to be a potential source of contamination at the LLWR.

The Sellafield site is a potential source of contamination as a result of discharge to the marine environment. Radioactive particles have been found on the Cumbrian coast and have been linked with releases from the Sellafield site including fuel-derived fragments originating from historic fuel handling and reprocessing activities. Similar particles would not be expected to originate from the LLWR site. Furthermore, release of particulate material from the LLWR discharge line is subject to a limit specified in the authorisation of 300 mg l^{-1} suspended solids. Discharges from the former Marchon phosphate processing works near Whitehaven are also identified as a historical source of radionuclides in the environment [35].

A layer of radioactive contamination derived from aerial sources related to the Chernobyl incident may also be present at the LLWR site. The 2010 '*Radioactivity in Food and the Environment*' (RIFE) report [36] provides detailed data and commentary on Chernobyl fallout as a source of environmental radioactivity in the UK. The report confirms that Chernobyl-derived Cs-137 was still detectable in:

- freshwater fish from upland lakes;
- terrestrial foodstuffs such as crops and meat;
- milk samples collected across the UK;
- airborne particulates and rainwater.

The report notes that levels had declined significantly since 1986, but that monitoring continued due to persistent residues in certain environments.

It is also expected that agricultural practices, particularly the use of nitrate fertilisers in the vicinity of the LLWR, will have an effect on groundwater and surface water quality.

2.5 Pathways

2.5.1 Releases to Air

Non-radiological and radiological releases to air have the potential to occur from the trench and the vault disposal areas. Permitted discharges also occur, via High Efficiency Particulate Attenuation (HEPA) filtered stacks, from the DGF, B746 and historically from the facilities for the retrieval of PCM from the magazines, the last of which were decommissioned in 2019. The trenches and vaults can be considered to be large area sources, although the former comprises localised points of discharge, the trench probe holes.

Continuous monitoring of gaseous discharges from the remaining two active discharge stacks is undertaken as part of the environmental monitoring programme so that we can assess the activity discharged and the performance of the filtration systems. Gaseous discharges from LLWR facilities are considered to be insignificant [37].

Discharged gases and any particulates will be subject to dispersion in the atmosphere. The local characteristics of the dispersion are influenced by the coastal setting and mixed surface characteristics, from heavily wooded areas to bare ground. Gaseous emissions from the site have no significant thermal energy or momentum, so there are no buoyancy effects.

Asbestos is known to be present in the near-surface soils across the site due to ROF activities [30]. It is therefore possible that asbestos fibres could become airborne if the ground is disturbed or they could be blown by the wind if these materials dry out and begin to break up. Controls on excavations are in place on the site to minimise potential mobilisation of asbestos fibres [38].

2.5.2 Releases to Surface Water

Currently, the main pathway for aqueous discharges of radionuclides is the Marine Pipeline, which discharges collected effluents to the Irish Sea approximately 1.2 km offshore. Radionuclides released via this pathway are rapidly dispersed, although a portion may sorb onto sediments.

The Drigg Stream crosses the western section of the site parallel to the south-western site boundary, joining a second stream, the East-West Stream, in the centre of the site. The Drigg Stream is partially contained in a deep, man-made channel and forms a tributary of the River Irt, discharging into the Ravenglass Estuary 320m south of the site.

The historical presence of elevated tritium activity in the railway drain and subsequently in the East-West Stream indicated the presence of a pathway from the trenches to the railway drain [39, 24]. The presence of tritium in this location prompted the construction of the bentonite cut-off wall along the northern and eastern flanks of the trench disposal area (Trenches 1 to 6 in 1988 and extended along Trench 7 in 1995). Current and historical monitoring data from the railway drain, since 1985, has shown that levels have significantly reduced over time, indicating that the pathway no longer allows the migration of contaminants.

Slightly elevated tritium activity has been detected in the Drigg Stream surface water, at the Lonesome Pine Weir and OF1 Weir during periods of low rainfall [40, 41]. The base of Trench 1 is at ground level to the south, which may allow leachate to migrate via old railway drains or groundwater to surface water. The sources of activity are currently being investigated. The activity levels reported are not replicated in the surface water samples collected at the GD0011 Weir, prior to the exit point of the Drigg Stream from the LLWR site.

Drigg Stream is known to contain sediments with an above background level of radioactivity. The sediments are a result of the authorised discharge of leachate directly to the stream prior to the construction of the MHT in 1991. During storm and flood events there remains the potential for the sediment to become suspended and migrate off-site [42].

2.5.3 Releases to Groundwater

Contaminants from the site have the potential to migrate into the groundwater that flows laterally and sub-vertically in a south-westerly direction towards the coast. It has been established that tritium and carbon-14 have undergone such migration indicating the presence of viable pathways from the trench disposal area. Only one borehole by the MHT shows evidence of migration of contaminants into groundwater from ROF activities or other land contamination in the form of low levels of hydrocarbons.

2.5.4 External Irradiation

Wastes on the site emit radiation. The main factors in determining the dose rate at any given point include the radionuclide concentrations in the wastes, the radiation geometry, distance and presence of any shielding. Because the site area is large in relation to an individual point of exposure, radiation doses will be dominated by the source that is immediately adjacent to the individual exposed (i.e. an individual trench or vault).

3 Regulatory Background and Approach

3.1 Regulatory Requirements

As noted in Subsection 1.1, the GRA sets out the need to monitor for changes caused by construction, operation and closure of the facility (Requirement 14).

According to the GRA, monitoring is:

> 'Taking measurements so as to be aware of the state of the disposal system and any changes to that state. This may include measuring levels of radioactivity in samples taken from the environment and also measuring geological, physical and chemical parameters that are relevant to environmental safety and that might change as a result of the construction of the disposal facility, waste emplacement and closure.'

In describing this Requirement, the guidance goes on to indicate that the approach to developing the environmental monitoring programme should be reasoned and proportionate. In the discussion of GRA Requirement 14, several subsidiary requirements are set out. Relevant material to these requirements is presented throughout this report. A summary of how we have addressed the requirements is provided in tabular form in the *Addressing Regulatory Requirements* report [18].

This report also contributes to addressing GRR Requirement 8 'Site characterisation and monitoring', which aims to ensure operator programmes support the information requirements of the WMP and SWESC. GRR Requirement 8 sets out that operators should establish a proportionate approach to site characterisation and monitoring that uses appropriate assessments to guide further investigations of land contamination, taking into account the nature of operations and former operations on site.

The Environment Agency has also issued updated guidance for environmental radiological monitoring [43]. The document outlines how to define objectives, design programmes, select sampling and monitoring techniques, and report results while considering proportionality, sustainability, health, safety, welfare, and quality. It covers principles and advice on programme design, including recommendations for measurement numbers, noting that not every type of measurement is necessary in all cases. The guidance focuses mainly on monitoring authorised discharges and is particularly relevant to the LLWR's permitted activities. The approach used to define the LLWR's monitoring programme is set out in this section and is based on an objectives-driven approach which included consideration of the draft guidance and its relevance to the LLWR monitoring programme.

Guidance on the environmental monitoring of radioactive waste disposal and safety case development is also covered in a series of International Atomic Energy Agency (IAEA) documents both published and draft [44, 45, 46]. The IAEA set out overarching objectives for monitoring and surveillance activities at radioactive waste disposal facilities.

- To demonstrate compliance with the regulatory constraints and licence conditions.
- To verify that the disposal system is functioning as expected. This means that the components fulfil their functions, as identified in the safety assessment and that actual conditions are consistent with the assumptions made for post-closure safety.
- To strengthen understanding of aspects of system behaviour used in developing the safety case for the disposal facility and to allow further testing of models predicting those aspects.
- To accumulate an environmental database on the site of the disposal facility and its surroundings for future decisions, which are part of a stepwise programme of disposal facility construction, operation and closure.

In developing our programme of environmental monitoring, we have also taken account of learning from other relevant operators and international best practice. This has included visits to peer facilities including in Spain, Canada, France and Slovenia to understand how monitoring is used to evaluate the safety of those facilities. We have contributed to the recent IAEA publication on the management of trenches containing historic radioactive wastes [47], which sets out the importance of long-term monitoring in decision making. We have a technical co-operation agreement with Andra/ENRESA/ONDRAF on engineered caps for near-surface facilities. Recent work has focussed on research into monitoring of erosion of soil layers which will be used to inform future monitoring arrangements for the final cap. We have also contributed to an IAEA guidance document on closure engineering of near-surface disposal facilities including monitoring considerations, which is currently under publication [48].

3.2 Permitting Requirements

The GRA (Requirement 14) requires us to monitor for changes to the environment caused by construction, operation and closure of the facility. These requirements are met by undertaking a prescribed monitoring programme agreed with the Environment Agency, as specified in the Compilation of Environment Agency requirements (CEAR) [49], regulated under Regulation 13 of the Environmental Permitting (England and Wales) Regulations 2016.

The monitoring schedule is reviewed annually and agreed with the Environment Agency. We have maintained a close relationship with the Environment Agency throughout the process of developing regulatory requirements, which has continued during the course of monitoring programme development.

We also undertake to ensure compliance with the Water Resources Act (1991), which details requirements in relation to three discharge consents:

- Discharge Consent Permit No. 017490347, which governs the release of treated sewage from two on-site treatment plants (STP1 and STP2).

- Discharge Consent No. NPSWQD002191 is a variation of a consent to discharge leachate from the LLWR site to the Irish Sea covering non-radioactive discharges, including leachate and minor arisings.
- Permit EPR-QB3298AJ was introduced to allow the use of flocculants for treating surface water during construction phases. This supplements the Sustainable Urban Drainage System and is applied case-by-case depending on rainfall and site activity.

For radioactive aqueous discharges, our Radioactive Substances Regulation (RSR) permit allows discharge via the Marine Pipeline with no radioactive disposal limit, provided Best Available Techniques (BAT) are used to minimise impacts. Discharge limits are set on Total Suspended Solids, Chemical Oxygen Demand, Iron, pH and visible solvents. Monitoring is required to ensure that no consent limit is breached and that there is continued evidence of the LLWR having minimal environmental impact.

In UK legislation, the Ionising Radiation Regulations 2017 requires Nuclear Licensed Sites to make arrangements to estimate doses to the Representative Person, where the Representative Person is ‘an individual receiving a dose that is representative of the more highly exposed individuals in the population’ [50]. These requirements are placed on Nuclear Licensed Sites by the Environment Agency under the Environmental Permitting (England and Wales) Regulations 2016. It is required that dose limits for public exposure are compared with the sum of annual exposures of the Representative Person resulting from all authorised practices (i.e. doses arising from historical and current discharges of radioactive waste and external irradiation exposure from the source).

The UK Government and Devolved Administrations have directed the Environment Agency to have regard to specific maximum doses to individuals that may result from a defined source, for use at the planning stage in radiation protection. The GRA [19] describes these requirements and specifies a 300 $\mu Sv\ y^{-1}$ dose limit from any source from which radioactive discharges are made.

3.3 Regulatory Liaison and Reporting

Meetings are held between staff from NWS and the Environment Agency once every two months. The monitoring programme is an agenda item for discussion at all of these meetings.

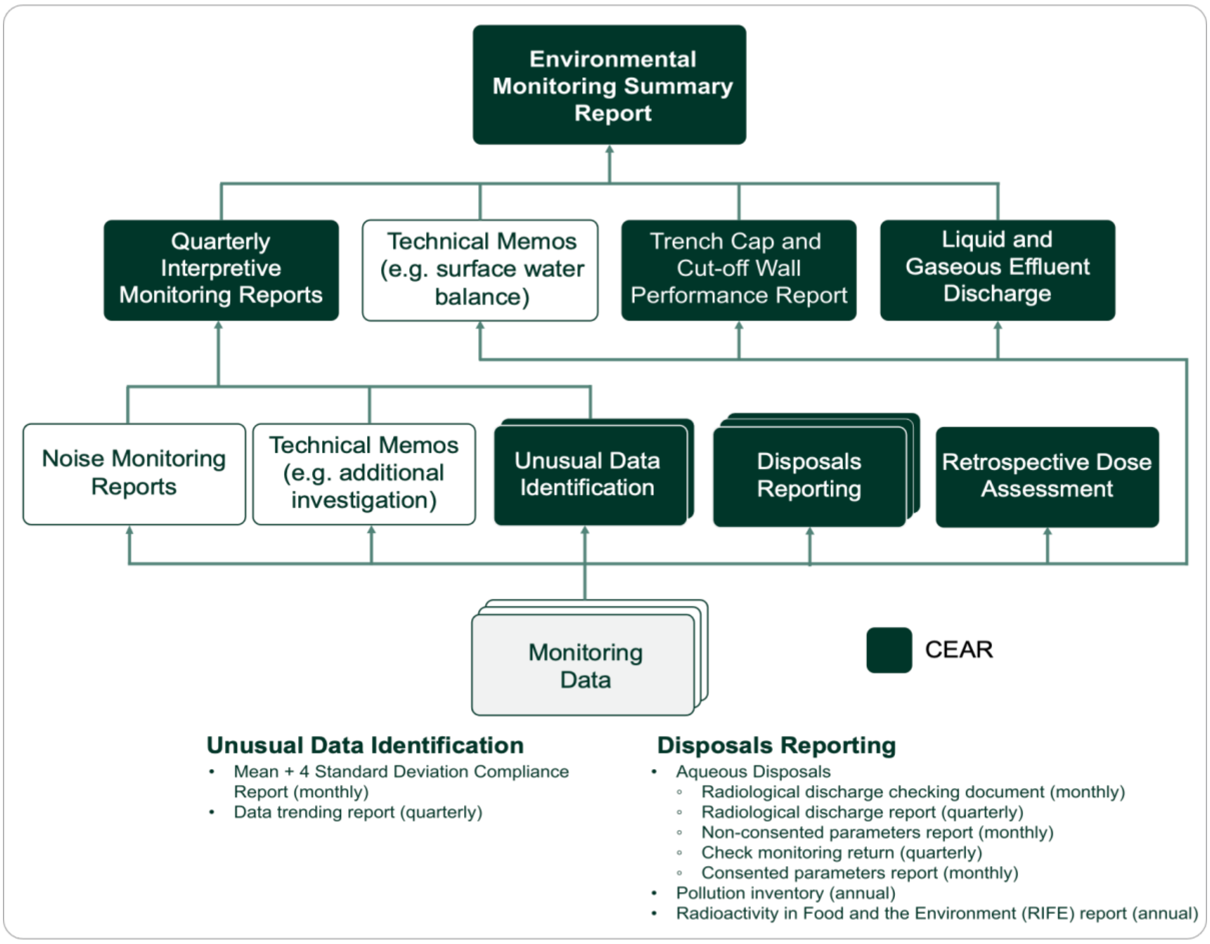
A review of the environmental monitoring programme reporting structure was undertaken during 2017 in conjunction with the Environment Agency [51]. The review identified that duplication of reporting was occurring, and this was rationalised. Changes were also implemented to enhance the environmental monitoring data review process. This allowed additional scrutiny of data as well as faster identification and investigation of unusual data and trends.

Reporting of the LLWR environmental monitoring programme to the Environment Agency is aligned with the annual monitoring cycle of April to March.

As detailed in the CEAR [52], the Permit specifies the need for an annual review of the monitoring programme to be provided to the Environment Agency. The scope of the review concerns the statutory monitoring programme and includes the following.

- *a description and interpretation of the entire environmental monitoring programme undertaken during that year to show how the monitoring results have been used to inform risk management options for the site and build confidence in the safety assessment models that underpin the ESC;*
- *review and development of the monitoring objectives;*
- *review of the scope and frequency of sampling (including both radionuclide and non-radionuclide analysis) against the monitoring objectives and consideration of past monitoring results and assessment (using statistical techniques, as appropriate), developments in best practice, developments in the operations/ environmental restoration at the LLWR and any other relevant issues;*
- *consideration of whether the sampling, measurements, tests, surveys, analyses, calculations and assessment techniques used represent BAT;*
- *review of the reasons why any:*
    - *results are late;*
    - *samples have not been obtained;*
    - *analysis was not undertaken;*
    - *relevant detection limits have not been achieved;*
    - *radiological assessments have used alternatives to the values and relationships given in reference* [53]. *The alternative data used shall be provided.*
- *recommendations for improvements (to the routine and investigatory elements of the environmental monitoring programme), where appropriate;*
- *clear identification of analytical results exceeding the mean plus four standard deviations (mean +4SD) of the previous 12 results and monitoring results that exceed the LLWR data quality flags. As far as practicable, an explanation shall be provided for any such elevated value;*
- *the type(s) of instrument used for contamination monitoring shall be specified.*

Throughout each monitoring period, several technical reports and memoranda are produced. A summary report, which collates the findings of the interpretations and assessments in these reports, is submitted the Environment Agency annually. Figure 3.1 identifies the current reporting structure for environmental monitoring data. Reports highlighted in green identify where these are requirements of the Permit and CEAR.



Unusual Data Identification

- Mean + 4 Standard Deviation Compliance Report (monthly)
- Data trending report (quarterly)

Disposals Reporting

- Aqueous Disposals
  - Radiological discharge checking document (monthly)
  - Radiological discharge report (quarterly)
  - Non-consented parameters report (monthly)
  - Check monitoring return (quarterly)
  - Consented parameters report (monthly)
- Pollution inventory (annual)
- Radioactivity in Food and the Environment (RIFE) report (annual)

Figure 3.1: Environmental monitoring programme reporting structure

3.4 Monitoring Programme Objectives and Requirements

We define the following objectives for the environmental monitoring programme.

- To confirm that the repository system is not giving rise to unacceptable environmental hazards by direct measurement of its impacts.
- To assess whether the repository system is compliant with the relevant environmental standards.
- To develop and build confidence in the models of the repository system by collecting data that may be used to refine conceptual models or in model parameterisation, calibration or validation.
- To define baseline conditions before specific engineering developments or activities, such as the construction of a new repository component (for example, a vault) or the disposal of wastes at a particular location.
- To confirm that construction activities are not giving rise to unacceptable environmental hazards by direct measurement of their impacts.

- To provide reassurance to stakeholders that the system is safe and is evolving in a manner consistent with the models and assumptions in the ESC.
- To monitor and identify any impact of land contaminated by historical operations on groundwater and surface water.
- To provide information needed to support the development of a WMP and SWESC.
- To work towards a programme that provides technical confirmation of the site reference state (e.g. include validation monitoring outline plans).

These are similar to the objectives set out by the IAEA (see above) and encompass many of the objectives set out in the Environment Agency monitoring guidance [43].

These objectives are met through an integrated monitoring programme that is subject to annual review and supported by a BAT assessment carried out in 2021 [54]. A two-tier approach to the BAT assessment of the monitoring programme was undertaken. The initial assessment was undertaken on the scope of the monitoring programme; what sampling and monitoring is undertaken, where and how often and if this scope demonstrates BAT with regard to the level of monitoring detailed within the Environment Agency monitoring guidance [43]. A further tier of assessment was then undertaken on the sampling techniques adopted for each element of sampling and monitoring within the monitoring programme and whether each of these techniques can be regarded as BAT. Additional information on the analysis of results, laboratory used, and the management and control of the monitoring programme was then provided to underpin the overall approach and execution of the monitoring programme carried out each year at the LLWR. The BAT is reviewed as part of annual review and updated periodically as required.

Management systems are in place to ensure that monitoring data are recorded and interpreted in an appropriate manner and due consideration is given to the investigation of anomalous data such as the groundwater mound or elevated tritium levels in Drigg stream. These aspects are addressed in more detail in the following subsections.

Environmental monitoring plays a particularly important role in the safety case for the PoA [13]. Over this period, direct confirmation can be provided that the concentrations of contaminants in environmental media are sufficiently low and consistent with relevant standards and guidance levels. If any significant changes in the system were detected, then consideration would be given to the requirement for additional monitoring, analysis or remedial action. The monitoring programme therefore provides important reassurance that the system is safe over the PoA. Analysis of environmental monitoring data will also lead to improved models or improved model validation, which will lead to increased confidence in models of contaminant release and human exposure in the post-closure phase when safety can no longer rely on monitoring.

Final waste emplacement at the site is expected to be 2135 with final capping expected be completed by 2142. The site will remain under active institutional control for around 100 years, during which monitoring and remedial actions remain possible.

As part of the 2011 ESC, we undertook a review of the long-term monitoring strategy [55] and formed part of the development of the integrated monitoring programme. We have continued to consider the long-term monitoring strategy and commissioned a review in 2015 [56] of monitoring approaches and techniques that could be used to address the monitoring objectives. The review concluded that the monitoring programme at that time fulfilled the requirements. The outcome was used to select appropriate techniques and define long-term functional requirements [57] for each option and identify any future development or adaptation that may be required. In this case, long-term refers to monitoring that may be required at different stages of the site's operational and post-closure periods. This has informed development of the monitoring programme and has been used to inform the options assessment carried out as part of the capping operations programme, which considered how capping should be implemented. Capping Vault 8 and the northern part of the trenches will require modification and replacement of the existing environmental monitoring infrastructure as well as the construction of new environmental monitoring infrastructure. A further BAT study was undertaken to determine the preferred monitoring approach [58]. This required identification of all monitoring infrastructure affected by the works. The techniques to modify, replace or decommission the existing infrastructure without compromising the environmental monitoring strategy were also considered. The assessment concluded that there was no one-size-fits-all solution, but the general approach is to use the existing monitoring infrastructure up until the point that the monitoring infrastructure becomes inaccessible and to ensure that current monitoring infrastructure is decommissioned effectively without creating future preferential pathways. A select number of monitoring infrastructure points will be raised as part of capping in order to maintain the existing monitoring programme. New monitoring infrastructure will also be installed as required.

A further external review, commissioned in 2025 [59], confirmed that the current monitoring programme is generally effective, with most of the areas performing well and others offering opportunities for enhancement related with the changes that the site will go through over the following years as discussed in Section 7.

3.5 Management Systems

An effective management system is an important requirement in ensuring effective outcomes from the environmental monitoring programme. The management system for the monitoring programme forms part of a wider management framework that is outlined in the '*Management and Dialogue*' report [2]. We have developed a management strategy for monitoring [60] centred on the following principles.

- Development of a clear process to define the environmental monitoring programme.
- The maintenance of a regular review methodology to ensure the monitoring programme remains permit compliant, BAT and is able to respond to changing circumstances.

- The use of appropriate quality assurance systems and good practice in data acquisition, data review, interpretation and data recording.
- The provision of a durable system for recording acquired data and for making it available in an accessible format.
- The appropriate use of data produced by the monitoring programme.
- The development of defined assessment levels to prompt further data review where necessary.
- Assurance that the appropriate internal interfaces are developed between different teams with an interest in monitoring data.
- Liaison with the regulator at all stages of the process.
- Ensuring that Suitably Qualified and Experienced Personnel (SQEP) are used and that there are intelligent customer capabilities within NWS.
- Effective asset management to ensure that monitoring points are maintained, remediated where necessary and decommissioned appropriately.

Each stage of the implementation of the environmental monitoring programme is controlled by procedures to ensure that all monitoring data are stored, verified and managed appropriately. The full procedures relating to environmental monitoring are provided in reference [60].

Quality assurance is applied and maintained by the use of method statements, ensuring that staff are SQEP, ensuring equipment is calibrated, use of data receipt procedures and the use of externally accredited contractors in the analysis of environmental media. Data are subject to internal validation and are held in a secure database system. Data import, verification, export, report production and review are managed through a NWS guide [61].

In order to consider the potential implications of any monitoring data to the ESC, bi-annual meetings are held between the ESC and Monitoring teams. This provides a forum for consideration of any significant breach of assessment levels (see Subsection 3.6) or new information from the assessment models or revised interpretation. In addition to these scheduled meetings, there is a formal process for the assessment of new information [62] that may become available outside the regular review cycle. This process ensures that any emerging data, research findings, regulatory guidance, or operational experience are systematically evaluated for their potential impact on the ESC and associated arrangements. Additional work would be triggered only where new information indicates a potential impact on safety. Breaches would also be reported via normal site sentencing and event reporting procedures, with appropriate management investigation as required.

In order to carry out the environmental monitoring programme, a wide array of infrastructure is in place across the LLWR site. Maintenance of this monitoring infrastructure is included in the Asset Care Programme. Regular visual inspections of the infrastructure are undertaken in conjunction with monitoring visits. If monitoring infrastructure becomes unusable then attempts will be made to remediate or recondition the infrastructure so that the monitoring point is retained. If boreholes become unusable or need to be removed then they will be decommissioned in line with Environment Agency guidance.

Environmental monitoring infrastructure is classed as Environmental Equipment as defined by the Environmental Permitting (England and Wales) Regulations 2016 and must be maintained to meet legal and regulatory standards. This designation refers to any equipment that provides an Environmental Protection Function. This function supports compliance with the ESC, environmental permits, or relevant legislation. The Environment Agency defines an Environmental Protection Function as:

> *'A function that is necessary to a facility for the avoidance or minimisation (or both) of radiological impacts to people and the environment.'*

Environmental Equipment is subject to examination, maintenance, inspection and testing (EMIT), tracked via the Computerised Maintenance Management System as specified in the NWS Asset Management Topic Manual [63]. The schedules for such are reproduced in the Environmental Clearance Certificate [64].

3.5.1 Information Management and Data Recording

As part of the integrated monitoring programme, an in-house database management system has been developed using a SQL (Structured Query Language) server-based database administered through MonitorPro software. The Environmental Monitoring Database System is the central repository for all environmental monitoring data at LLWR. It is structured into three core databases:

- Time Series Data: physical measurements such as dips, levels, and flow rates.
- Analytical Data: laboratory and field test results.
- Land Quality Data: chemistry data from ground investigations.

This database is linked directly to data tabulation, graphing and GIS (geographic information system) software from which all data evaluation, figure and table construction can be undertaken. MonitorPro is used to generate statutory reports such as Quarterly aqueous discharge reports, to fulfil CEAR requirements.

Field data are collected both electronically and manually. Electronic data are downloaded and transferred to the central data file. All original files are retained as part of the audit trail, allowing the data to be re-checked if necessary. Where manual entry of data is used, the data are entered onto pre-defined record data sheets. These are then scanned and housed in a central data area prior to filing. The data are entered into a .csv format and checked prior to entry into the relevant database. Analytical data are provided by the laboratory in Excel reports directly.

Upon receipt, the data are processed in accordance with the internal data receipt and import Guidance document [61]. Data that are received are placed in a holding folder until the checking and import process can be carried out. MonitorPro automatically logs data file names as they are imported.

Data quality is of prime importance to the management of the monitoring programme at the LLWR. The verification process has been designed to ensure that the data are checked according to stringent standards. The data are checked internally (for simple, logical or technical errors) and externally (by comparing with field data and previous results from the same location, checking against quality control samples and through using contractors with external, quality accreditations).

Internal validation is achieved through the following verification procedures.

- Comparing data with field sheets.
- Checking the analytical data with the sample request sheets to ensure that the correct suite has been analysed.
- Checking the database values with other background information.
- Time series analysis of data from the same monitoring points.
- Checking of Quality Control samples where available.
- Checking equipment calibrations.

All sampling, analysis and reporting procedures are also verified using an external quality standard. We ensure that all contractors have achieved International Organization for Standardization (ISO) Quality Management System accreditation and that all testing laboratories are United Kingdom Accreditation Service (UKAS) accredited. Environment Agency Monitoring Certification Scheme (MCERTS) accredited laboratory methods are used where practicable.

3.6 Performance Measures

In order to review and assess the significance of data collected as part of the environmental monitoring programme, we undertake the following steps.

- ‘Unusual’ data are identified by comparison to Unusual Data Identification Levels (UDILs).
- Trends in the data are used to identify gradual changes (both positive and adverse).
- ‘Unusual’ data and adverse trends are assessed against performance measures, where required, in order to assess the significance of this data.

Where data are identified as exceeding relevant screening criteria, or following an unusual trend, this does not necessarily mean that operations at the LLWR site are impacting unacceptably on the environment. It does, however, allow the significance of the results to be assessed and further investigation instigated where appropriate.

3.6.1 Unusual Data Identification Levels

Mean +4 Standard Deviations (Mean +4SD)

Mean +4SD levels are automatically calculated for all analytical data where at least five previous data values exist. Results exceeding the Mean +4SD threshold are investigated and reported to the Environment Agency on a monthly frequency.

Data Quality Flags

Data Quality Flags (DQFs) are statistical thresholds used to identify environmental monitoring data that fall outside the expected or 'usual' range. At LLWR, DQFs are applied to both field measurements and laboratory data to:

- detect adverse trends or anomalies;
- trigger investigations when values exceed predefined thresholds;
- support regulatory reporting and internal performance reviews

DQFs for field measurements are defined for an individual sampling location, whilst DQFs for laboratory data have been defined for each environmental system. DQFs have been statistically calculated from baseline datasets, unless overarching regulatory levels are applicable. Prior to calculating DQF values, the baseline data are sampled to extract data within three standard deviations of the mean. It would therefore be expected that 5% of the results should exceed or be below the DQF. In some cases DQFs are defined to identify data that are outside the ‘usual’ data range for an individual location, e.g. stream levels below weir level. DQFs are also sometimes based on guidance values. Data identified as exceeding a DQF can then be reviewed and further investigation undertaken. The DQF levels are regularly reviewed and revised levels are implemented at the start of the monitoring year [65].

All laboratory analysis results are calculated in accordance with ISO11929 [66] whereby a decision threshold and Limit of Detection are calculated for each measurement. The decision threshold is the minimum measured value at which you can state, with a defined confidence level, that the result is above background (i.e., a true signal). The ISO11929 method requires that any result above the decision threshold is reported as a positive detect, even if it is below the Limit of Detection. Numerical values below the Limit of Detection are presented to allow trend analysis but are not interpreted as confirmed detections. Where such data are used in dose assessments, conservative assumptions are applied by bounding concentrations between zero and the Limit of Detection.

3.6.2 Trending

Charts showing the change in the values of various parameters as a function of time are produced on a quarterly basis for all numerical data collected during the previous quarter. These charts allow the visual identification of adverse trends at a location, which may not be captured as an ‘unusual’ data point (i.e. if a trend is increasing at a rate that did not trigger a

Mean +4SD exceedance and is below the DQF value). Internal trending reports are produced quarterly for review [67, 68].

3.6.3 Performance Measures

Screening criteria have been identified to assess the impact of LLWR site operations, including disposals, on river water, surface water and groundwater.

LLWRAS

For radiological groundwater quality and all river water and surface water quality laboratory results, measured concentrations are compared with Low Level Waste Repository Assessment Standards (LLWRAS).

The current groundwater radiological LLWRAS were introduced during 2019 [69]. They apply the Environment Agency's supplementary guidance [70] related to the implementation of the Groundwater Directive [71], which describes a requirement to protect groundwater from radioactively contaminated discharges. This requires LLWR to demonstrate that the dose to members of the public from the groundwater pathway during the PoA is consistent with a radiation dose of 20 μSv y^{-1} [71]. Although groundwater is a receptor in its own right, we seek to demonstrate that we protect groundwater by calculating radiological impacts to members of the public and non-human biota who potentially interact with groundwater during the PoA and thereafter. The Environment Agency [72] advises that an input of a radioactive substance to groundwater during the PoA is considered to have been prevented if:

- the radiation dose to members of the public incurred via the groundwater pathway is consistent with, or lower than 0.01 mSv y^{-1}; or,
- if the radiation dose exceeds 0.01 mSv y^{-1}, to demonstrate that:
    - the dose to a representative person through all pathways during the Period of Authorisation is less than 0.3 mSv y^{-1}; and,
    - doses are as low as reasonably achievable, taking into account economic and social factors (i.e. the repository and the waste management arrangements are optimised); or,
- the concentration of radionuclides (in Bq l^{-1}) attributable to the discharge in groundwater immediately down-gradient of the discharge zone is consistent with background concentrations in this or a similar geological formation.

The calculation addresses all exposure pathways potentially associated with use of a water abstraction well i.e. including consumption of water and contaminated animal products. The assessment of the groundwater pathway during the PoA [13] only considers dose from consumption of abstracted well water. These LLWRAS are also utilised to assess the impact of the LLWR on river and surface water quality as the predominant exposure pathway aligns with that for groundwater (water for livestock) [14]. We recognise that although the 20 μSv y^{-1} level is consistent with the previous guidance [70] it is higher than the 10 μSv y^{-1}

level provided in the new guidance issued in 2021 [72] and will review the radiological LLWRAS accordingly.

For consistency with radiological aspects of the ESC, we define Environmental Assessment Levels for non-radiological contaminants in water in terms of LLWRASs. For hazardous substances, the LLWRAS is taken to be the most restrictive of:

- the Environmental Quality Standard (EQS);
- EU Drinking Water Directive (DWD) standards [73]
- the MRV, which are taken, where possible, from the official Environment Agency list [73];
- the Limit of Detection.

For non-hazardous pollutants, LLWRASs for non-radiological contaminants are currently based on the most restrictive EQSs for fresh water or salt water [73]. Where no EQS is available, the EU DWD standards [73] are used. LLWRASs are reviewed on an annual basis to ensure they align with any changes to the respective standards.

Where an EQS is quoted as a range of values, the LLWRAS is calculated based on the EQS designated limiting value, usually water hardness, during each monitoring campaign. The quantitative HRA utilises the minimum EQS value against which to assess calculated concentrations in groundwater.

Monitoring Assessment Levels (MALs)

The LLWRAS do not take account of background concentrations of contaminants and, as such, exceedance of the LLWRAS is not necessarily an indication of pollution as background levels may already exceed the LLWRAS. To address this we have defined MALs, which are used within the monitoring programme to assess the measured contaminant concentrations in surface water and groundwater. The MALs are set to be the highest of the LLWRAS and the level discernible above background.

MALs are used to assess the impact of non-radiological contaminants from the site, including disposals, on groundwater. The discernible level has been calculated at the 95th percentile of the background dataset. The use of MALs is intended to reduce the number of false positives [74].

MALs explicitly take account of background, because they are defined as the higher of the assessment standard or the level discernible above background, typically set using the 95th percentile of the background/baseline dataset. But individual results can still exceed the MAL due to natural variability, localised inputs, or transient conditions. An exceedance therefore flags “above what we would normally expect”, not “pollution from the site.”

Baseline water quality data

Baseline values have been derived for rainwater, river water and groundwater [75]. The baseline is the naturally occurring level of a contaminant measured prior to construction of a facility, or in the case of an existing facility, the level measured upstream of the site. For some contaminants, the baseline level may exceed the assessment standard.

Baseline and background are closely related but are not the same thing, even though they are sometimes derived from the same datasets. Baseline water quality represents a defined reference condition established at a specific time and location for regulatory assessment, whereas background water quality describes the broader ambient range of concentrations arising from natural and diffuse sources; the terms are therefore related but not synonymous.

Using a baseline provides a clear, fixed reference for assessing change, whereas relying on background alone would be ambiguous and variable, making results harder to interpret and defend when naturally high concentrations are present.

4 Monitoring Programme

The monitoring programme can be divided into the following areas:

- leachate, groundwater and surface water composition;
- leachate, groundwater, surface water levels and fluxes;
- gas composition and fluxes;
- LLW waste container evolution;
- engineered barrier performance (interim cap, final cap, cut-off wall etc.);
- reassurance monitoring (milk, grass etc.);
- supporting data (rainfall, wind speed, coastal evolution etc.).

There are multiple uses for the different monitoring elements. For example, groundwater monitoring provides current groundwater conditions in and around the site, but over an extended time period, it indirectly provides information on the migration and evolution of leachate and the performance of the engineered barriers. Others, such as weather data, provide information that can be used to assess the performance of the cap when combined with data on surface water and leachate levels as well as informing the 2026 ESC climate projections.

The monitoring programme is carried out on an annual cycle based on the financial year of April to March. The data collected are reviewed, assessed, and reported on a quarterly basis throughout the year. Every third year, enhanced monitoring is performed to capture a wider spectrum of sample points and a broader analysis suite for certain locations.

A wider suite of analyses for hazardous and non-hazardous pollutants, alongside radionuclides, is also undertaken on bulk trench and vault leachates on a triennial basis to understand if the composition is changing through degradation of the waste. The analysis includes Total Petroleum Hydrocarbon bands (C6–C40), aromatic/aliphatic fractions and individual Polycyclic Aromatic Hydrocarbons.

Findings from these analyses are used to inform changes to the environmental monitoring programme in subsequent years. Triennial bulked leachate analyses were carried out as part of the 2024/25 environmental monitoring programme. The reported results from the bulked leachate analysis to date have not identified any additional contaminants of concern that needed to be added to the environmental monitoring programme. Bulked leachate samples are composite samples created by combining leachate collected over a defined period and/or from multiple locations into a single, representative sample for analysis.

In addition to the environmental monitoring programme, site characterisation works are carried out to support the WMP, to develop our understanding of the impacts to the site from historical operations and in support of site operations where interactions with ROF infrastructure occur. Findings from these investigations are not detailed within this report but are addressed in the '*Hydrogeology*' report [7], however, adverse findings from monitoring to assess migration of contamination from these areas is discussed within the relevant sections.

The scheduled environmental monitoring programme for 2025/26 is recorded in the '*Site Environmental Monitoring Programme Schedule of Works*' [76]. A breakdown of the monitoring performed is shown in Figure 4.1. This is subject to annual review and will change from what is presented here but is shown as a useful snapshot in time to illustrate the extent of the monitoring programme. Table 4.1 shows summary analytical demands for the year for monitoring area.

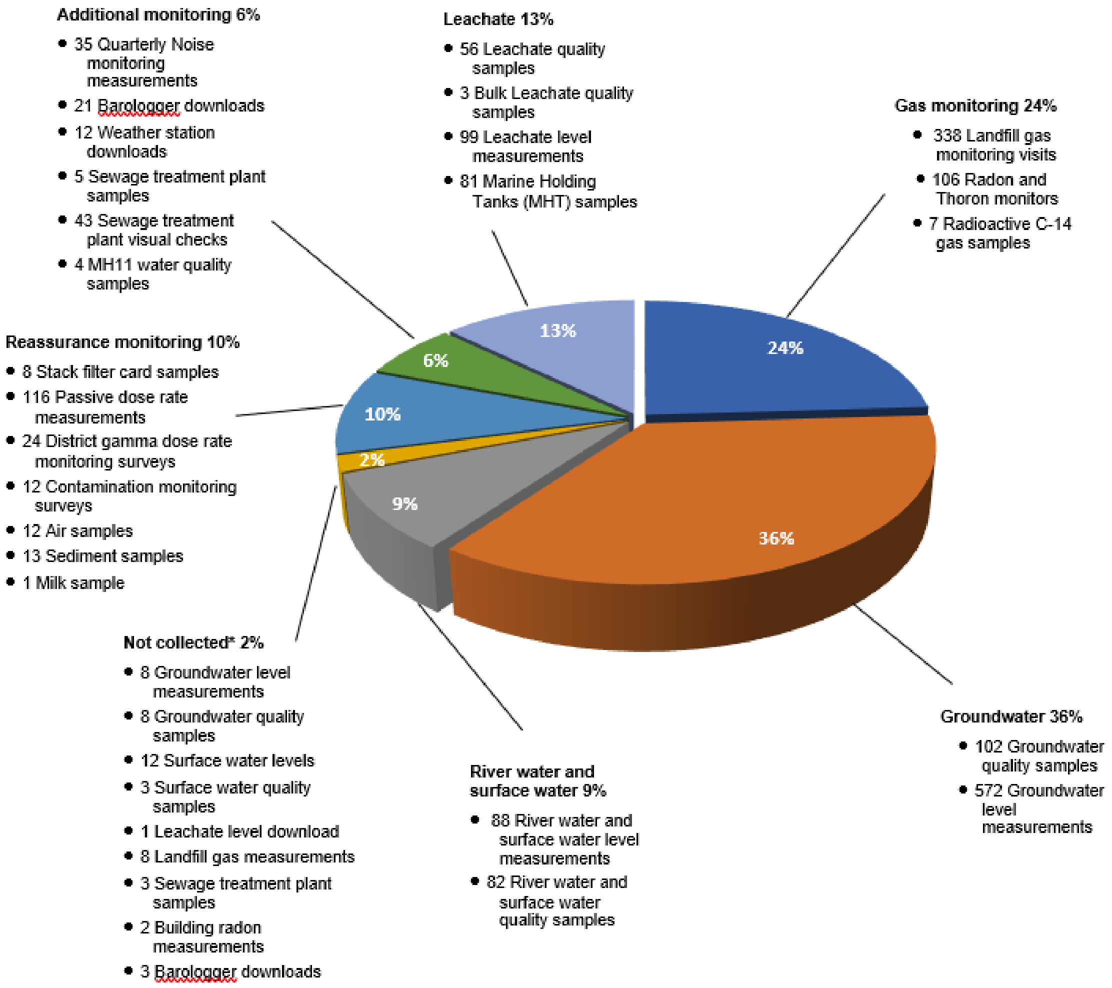


Figure 4.1: Proportional representation of the environmental monitoring programme 2024 to25

*** An explanation of why measurements were not made, or samples not collected, is provided in the annual monitoring report [37]**

Table 4.1: Analytical Determinands Required 2025/26

Parameter	Radionuclide	Non-radionuclides	Characterisation
River water Surface water	Total α, total β, total H-3 and γ-scan spectrometry.	Metals suite (As, Ba, B, Be, Cd, Co, Cr, Cu, Hg, iron as Fe, Mn, Mo, Ni, Pb, Se, V and Zn). Major ions suite (Ca, Na, K, Mg, Cl, sulphate, NO_2, NO_3 and HCO_3 (alkalinity)). Ammonia as NH_4, ammoniacal nitrogen, sulphide, total phenols, total cyanide and total organic carbon (TOC).	Conductivity, pH, temperature, biological oxygen demand (BOD) and total suspended solids (TSS)
Sea water		Metals suite (As, Ba, B, Be, Cd, Co, Cr, Cu, Hg, iron as Fe, Mn, Mo, Ni, Pb, Se, V and Zn).	Conductivity, pH, temperature, chemical oxygen demand (COD), visible solvent and TSS.
Rainwater	Total α, total β, total H-3 and γ-scan spectrometry.	Metals suite (As, Ba, B, Be, Cd, Co, Cr, Cu, Hg, iron as Fe, Mn, Mo, Ni, Pb, Se, V and Zn). Major ions suite (Ca, Na, K, Mg, Cl, sulphate, NO_2, NO_3 and HCO_3 (alkalinity). Ammonia as NH_4, ammoniacal nitrogen, sulphide, total phenols, total cyanide and TOC.	Conductivity, pH, temperature, BOD and TSS.
Groundwater	Total α, total β, total H-3 and γ-scan spectrometry, Total C-14, Sr-90, Cl-36 and Tc-99.	Metals suite (As, Ba, B, Be, Cd, Co, Cr, Cu, Hg, iron as Fe, Mn, Mo, Ni, Pb, Se, V and Zn).	Conductivity, pH, temperature, dissolved oxygen and redox potential.

Parameter	Radionuclide	Non-radionuclides	Characterisation
		Major ions suite (Ca, Na, K, Mg, Cl, sulphate, NO_2, NO_3 and HCO_3 (alkalinity)). Fluoride, ammonia as NH_4, ammoniacal nitrogen, sulphide, total phenols, total cyanide, NO_2, NO_3 and TOC. Dissolved organic carbon (DOC).	
Aqueous effluent	Total α, total β, total H-3 and γ-scan spectrometry Total C-14.	Major ions suite (Ca, Na, K, Mg, Cl, sulphate, NO_2, NO_3 and HCO_3 (alkalinity)). Fluoride, ammonia as NH_4, ammoniacal nitrogen, sulphide, total phenols, total cyanide and TOC. Iron as Fe, Cu	Conductivity, pH, temperature and COD, TSS and visible solvent.
Landfill gas	Total radon, C-14 and thoron.	Hydrogen, methane, carbon dioxide and oxygen.	
Sediment	Total α, total β and γ-scan spectrometry.	Metals suite (As, Ba, B, Be, Cd, Co, Cr, Cu, Hg, iron as Fe, Mn, Mo, Ni, Pb, Se, V and Zn) (samples from OF Weir only).	
Grass	Total α, total β, total H-3 and γ-scan spectrometry.		
Milk	Total α, total β, total H-3 and γ-scan spectrometry.		

Stack filters	Total α and total β.		
Ambient air	Total α, total β, γ-scan spectrometry (monthly). Total uranium α, plutonium α, Am-241 and Pu241 (annual).		

4.1 Aqueous Effluent (Leachate)

Monitoring of leachate level and quality is undertaken at several locations across the LLWR site. There are four components to this monitoring: trench cap probe holes, end-of-trench drains, vaults and the MHT. The trench cap probe holes are a series of monitoring points installed across the seven trenches to vent gas but also allow monitoring of the leachate. Each trench has a drainage point, or in the case of Trench 7 two points, at the southern end that incorporates a chamber to allow monitoring of leachate quality and flow. Vault 8 and Vault 9 are operational disposal areas with engineered drainage points for the collection of leachate (Figure 4.3). The MHT is shown in Figure 4.4. As the vaults are currently uncapped, the discharge is predominantly rainfall. The south-east drainage point in Vault 8 (MH17) is known to also collect leachate emanating from Trench 3 and, therefore, has a higher concentration of radioactivity than other Vault 8 monitoring locations.

4.1.1 Leachate Level and Flow

Flow rate and discharge volume are automatically recorded and calculated for each discharge from the MHT to the Irish Sea.

The Vault 8 pumping system is currently being refurbished. No discharge flow measurements are being recorded during the refurbishment works. The Vault 9 pumping system has successfully been refurbished, and the data are being downloaded on a quarterly basis. Collection of discharge flow data from Vault 8 will resume following the completion of the refurbishment works.

Leachate temperature and levels are important in providing information on the hydrology of the trenches and in understanding the potential influence of rainfall. Leachate temperature and level measurements are collected by automatic data loggers or through manual measurements with a dip tape. Automatic data loggers are installed in all trench cap probe holes that consistently contain more than 0.35 m of leachate.

During 2023/24, 31 of the 83 trench cap probe holes were permanently decommissioned in preparation for construction of the final cap. These locations are no longer available for level and temperature monitoring.

Flow rate and discharge volume have previously been recorded from each of the end-of-trench monitoring chambers and each of the pumping chambers in Vault 8 and 9. The data logging equipment in each of the end-of-trench monitoring chambers has reached its operational battery life expectancy. Measurements from these data loggers have been suspended and a replacement system is expected to be installed in 2027.

It will take a couple of years to design and replace the installed equipment and therefore a temporary system to measure the daily number of pump activations at each end-of-trench monitoring pit is to be installed in 2025/26. This system will monitor trends in leachate production at the end-of-trench monitoring locations whilst the new system is being designed and installed.

4.1.2 Leachate Quality

Leachate quality during 2024/25 was monitored in several locations in order to provide:

- an assessment of changes to the waste source term;
- data to allow review and reporting of authorised discharges to the environment;
- an assessment of field parameters (specific conductivity, pH and temperature).

Three field parameters are recorded during sampling of the leachate (temperature, specific conductance and pH). The field parameter readings are used to identify changes in the overall leachate system.

Discharges from Vault 8, Vault 9 and the end-of-trench leachate chambers have been sampled and analysed on a quarterly basis to provide information on the source term.

An extended suite of radiological and non-radiological contaminant analysis was carried out as part of the 2019/20 triennial ‘ramp-up’ year and several of these analytes were also repeated during the 2020/21, 2021/22 and 2023/24 monitoring years. This analysis was in part carried out to support a wider investigation into the presence of carbon-14 and strontium-90 in groundwaters, but also to augment the limited dataset that has been recognised for some analytes.

Bulked leachate samples are collected and analysed on a triennial basis from the trenches and each of the vaults. The sampling is undertaken to inform the monitoring strategy for non-radiological parameters that are conducted in the subsequent ‘ramp-up’ triennial year.

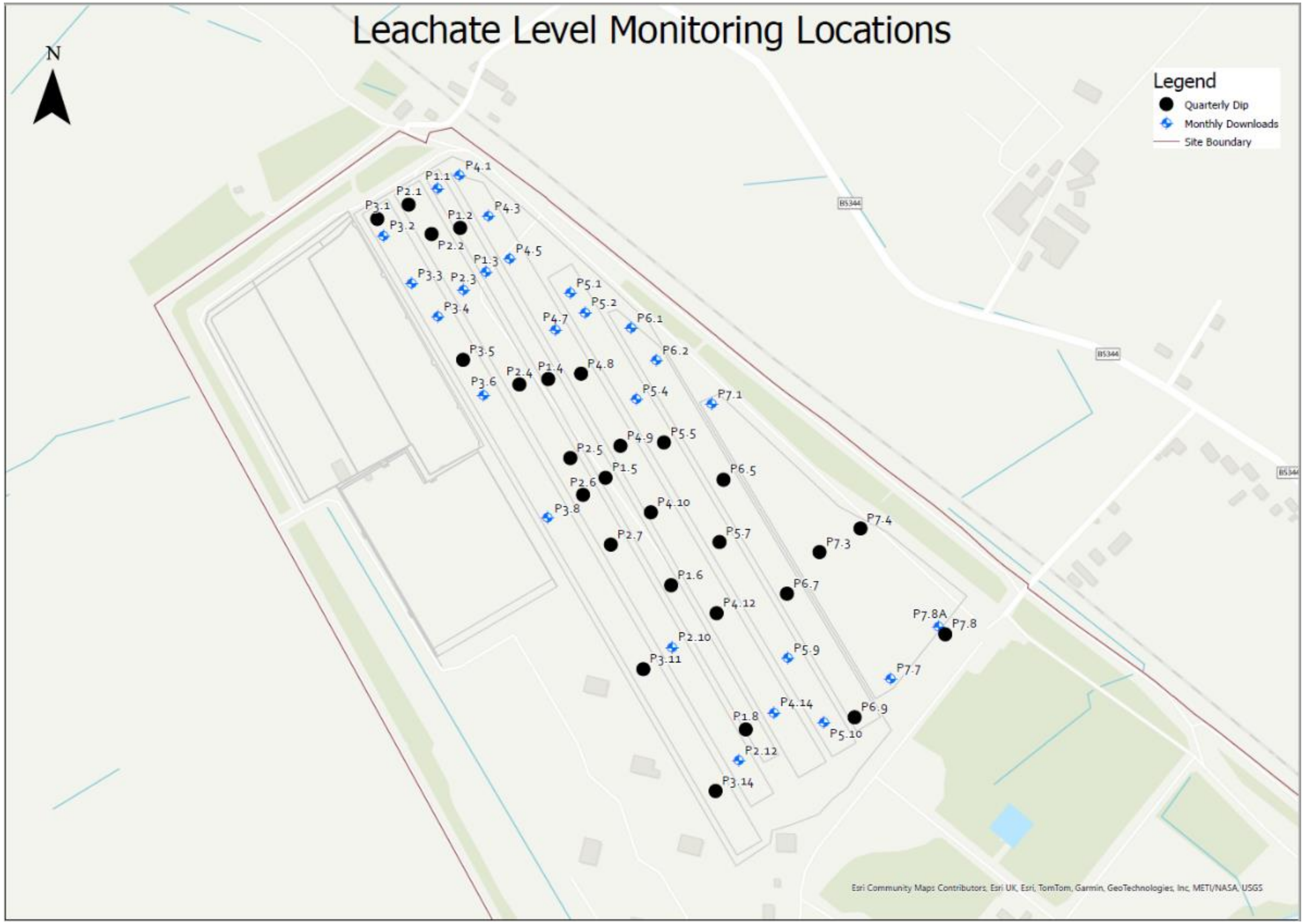


Figure 4.2: Trench leachate level monitoring (2025/26) [76]

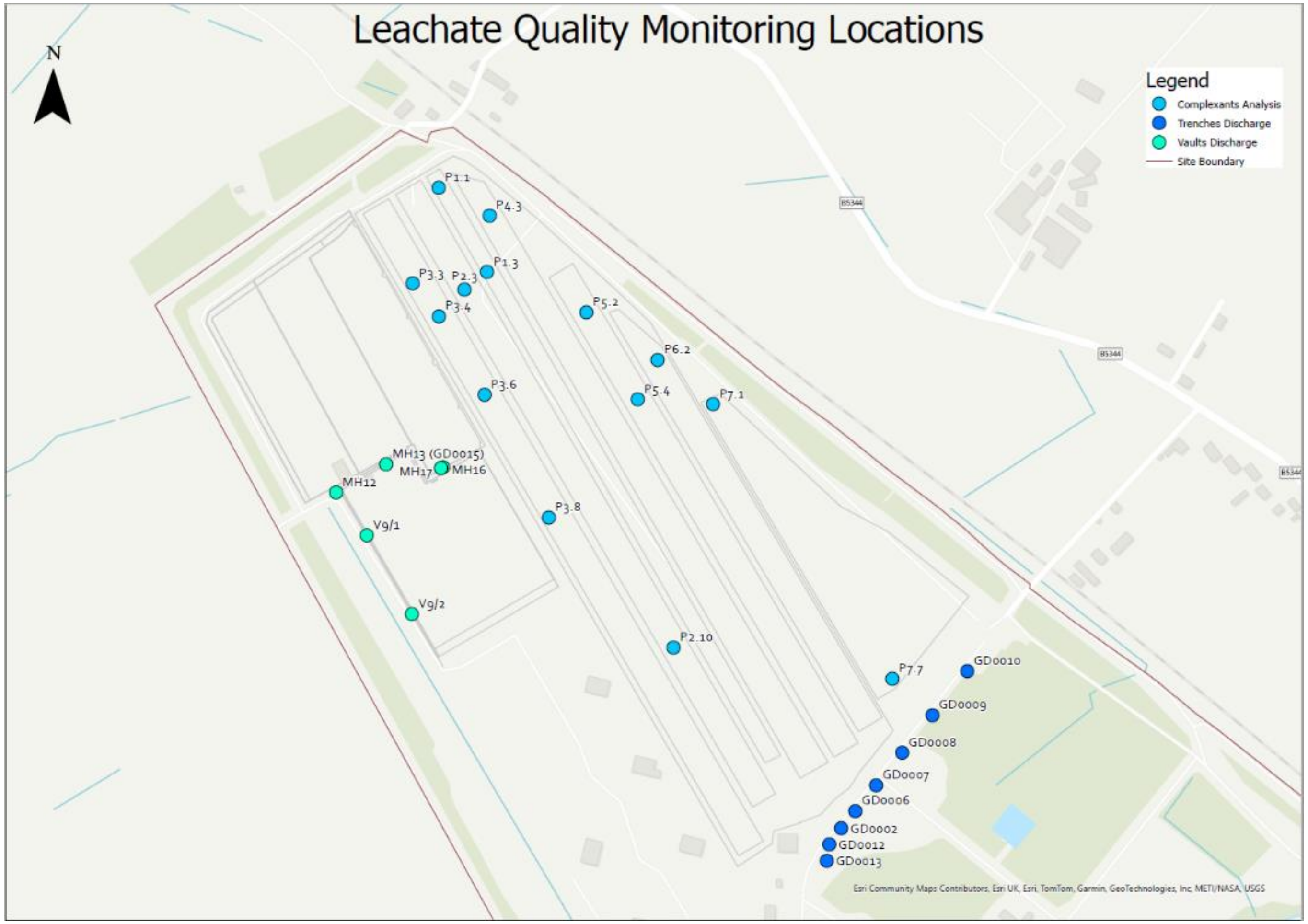


Figure 4.3: Leachate quality monitoring locations (2025/26) [76]

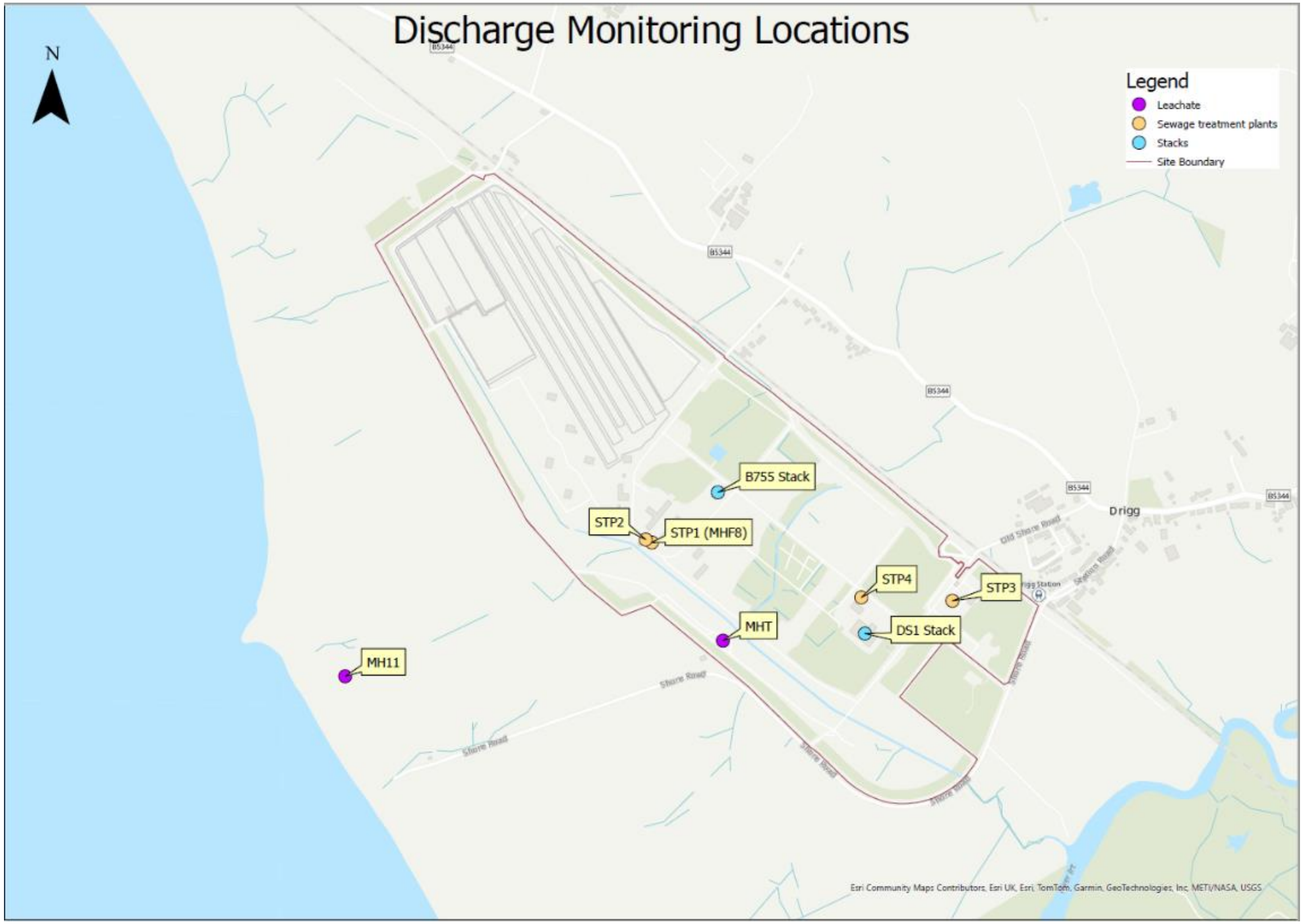


Figure 4.4: **Discharge Monitoring Locations [76]**

4.2 Groundwater Monitoring

The environmental monitoring programme is designed to assess the impact of the LLWR on the underlying aquifer by investigating groundwater quality and levels upstream of, on and downstream of the site. This is done through a network of groundwater monitoring wells that have been installed to target each of the groundwater systems at key locations. Groundwater level and chemistry data is used to inform the hydrogeological conceptual model and to calibrate groundwater flow models developed in support of the ESC, more details are provided in the '*Hydrogeology*' report [7].

4.2.1 Groundwater Level

Groundwater levels are measured across the LLWR site and surrounding area, both upstream and downstream of the site (Figure 4.5). Monitoring wells are typically named using a numeric location ID followed by a suffix p1, p2, p3 indicating paired or multiple installations at the same location, usually representing different depths or boreholes within the same monitoring cluster with p1 being the deepest and p3 the shallower.

Since the start of the 2020/21 monitoring year, the frequency of data collection from the groundwater automatic data loggers was reduced from fifteen-minute to six-hourly. The number of groundwater monitoring wells with automatic data loggers installed was also reduced, to focus principally on the disposal area and the downstream areas from it.

For the 2024/25 reporting period, groundwater level data were collected at the following locations and frequencies.

- 62 locations had automatic groundwater level data loggers installed, recording measurements at six-hourly intervals with data downloaded quarterly. Data loggers are installed in more locations than is required to provide sufficient redundancy to mitigate against data loss.
- 145 locations were manually dipped on a quarterly basis.
- Basal dip measurements of each well are carried out annually. The basal dips recorded are reviewed annually to establish if silting of the well is occurring and if redevelopment is required.

A technical memorandum is produced annually to record the quality assurance check of the groundwater level data collected and how the manually dipped water levels correspond to the levels recorded on the automatic data loggers.

4.2.2 Groundwater Quality

As part of the 2024/25 monitoring year, groundwater quality was monitored at 80 locations in order to:

- assess the impact of the LLWR on groundwater beneath and down-gradient of the site;

- monitor the evolution of the existing tritium and carbon-14 in groundwater to contribute to understanding of the overall system;
- assess any changes to our understanding of the groundwater systems in the wider site area;
- monitor the performance of the existing cut-off wall along the northern and eastern flank of the trench disposal area;
- monitor groundwater hydraulically up-gradient of the LLWR;
- monitor hydraulically down-gradient of potential areas of land contamination or construction work;
- supplement baseline datasets prior to construction work;
- identify any contaminants migrating from areas of land contamination.

Figure 4.6 and Figure 4.7 show the distribution of monitoring points for radiological and non-radiological analysis. These figures show sampling locations, type of analysis and frequency of sampling. The frequency is reviewed regularly and adjusted to investigate trends or reduced if no rapid changes are observed or where sufficient baseline data have been collected. The aim is to continue to monitor from existing wells to provide a continuous times series, however, some boreholes have become unusable over time due to silting or have been removed due to operational reasons (e.g. cap construction). New boreholes have also been constructed to support future developments providing wider coverage or sampling of deeper units.

The selection of the analytes is informed by the leachate analysis but also by the need to further the understanding of the non-radiological groundwater chemistry within the groundwater systems to support the ESC. Following a review in 2017 [77], a wider suite of non-radiological analytes has been targeted across the site, and at upstream and downstream locations on an annual basis. The data have been used to update the hydrogeochemical understanding of the LLWR site [29].

Figure 4.5: Groundwater level monitoring locations [76]

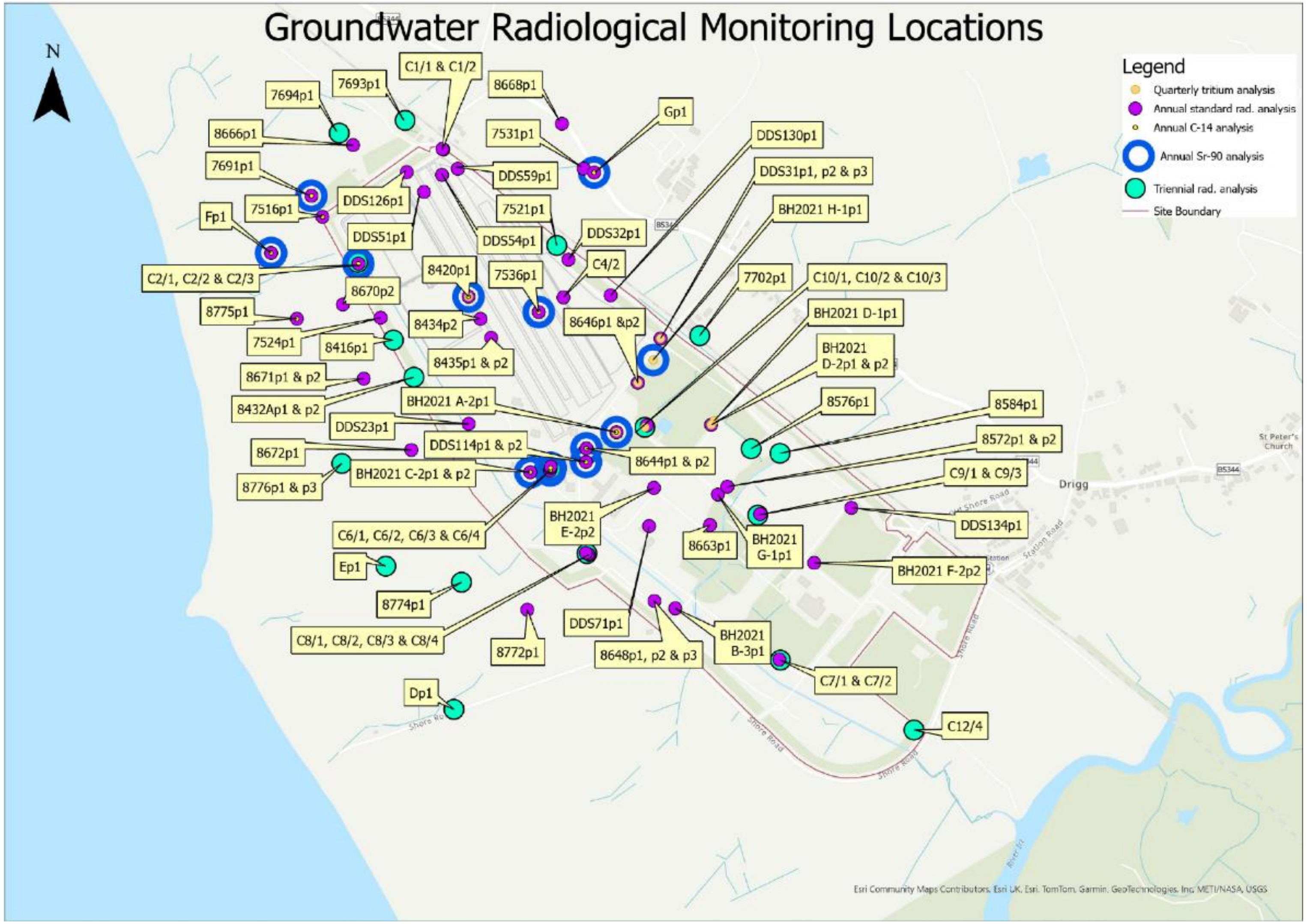


Figure 4.6: Groundwater radiological monitoring locations [76]

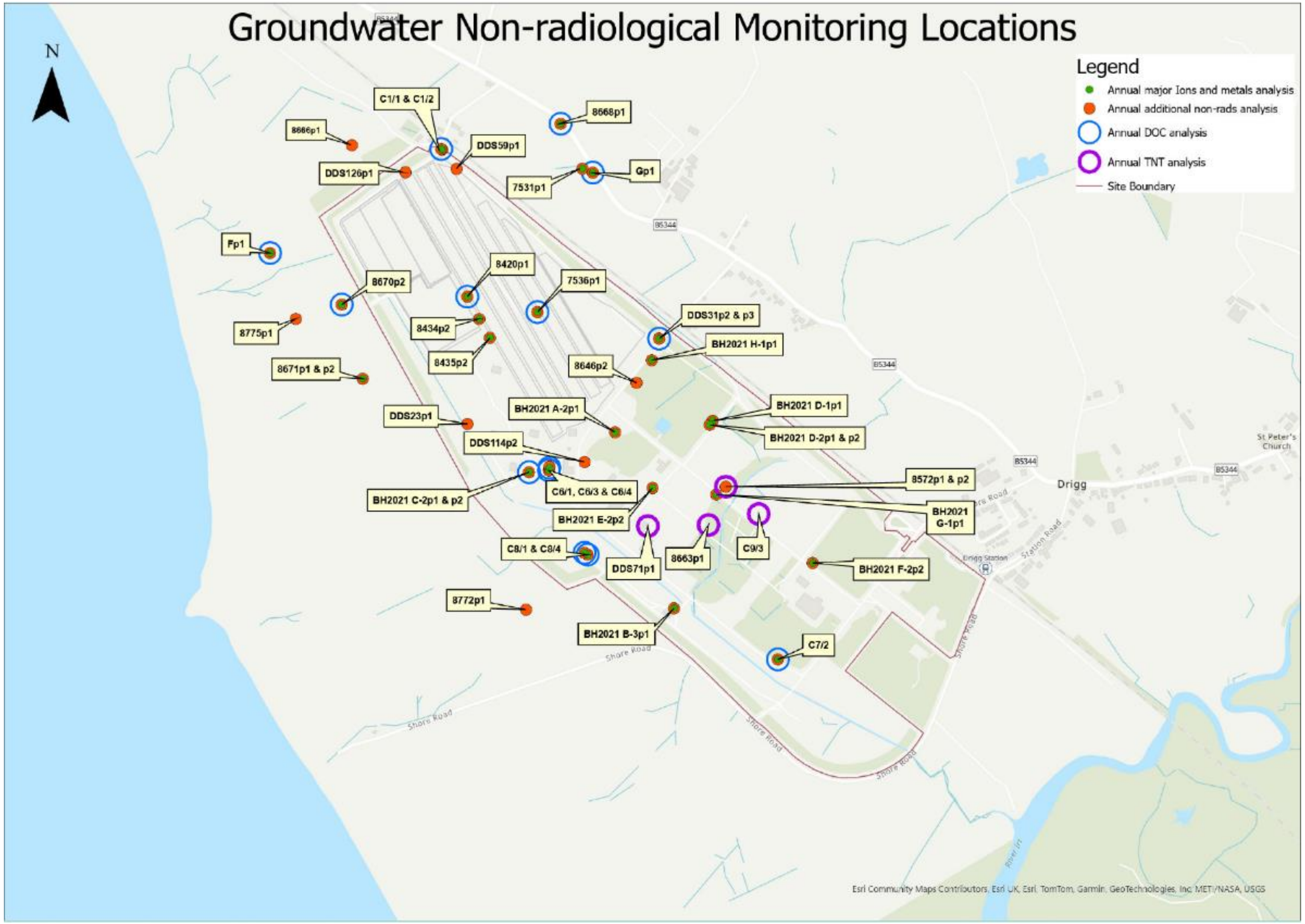


Figure 4.7: Groundwater non-radiological monitoring locations [76]

4.3 Surface Water

Water quality and flow measurements are made on both streams that flow through the site, surface water drainage from the trench cap and two land drains that enter the Drigg Stream. In addition, several water quality samples are collected from drainage channels, seepages, surface water bodies and the River Irt. These samples are collected to provide an overall understanding of the water balance across the site and to assess the potential impact of the site on water quality.

Two streams, the East-West Stream and the Drigg Stream, run through the LLWR site (Figure 2.1). Monitoring of water level and flow within each stream provides baseline information used in the assessment of engineered barrier performance [78]. Results are used to constrain water balance calculations and models of site hydrology [24]. Five locations along the two streams are monitored at fifteen-minute intervals using automatic data loggers. The locations are as follows: one weir on the East-West Stream (Frog Weir), two weirs on the Drigg Stream (Lonesome Pine Weir and GD0011 Weir) and two on-site land drain weirs discharging into the Drigg Stream (OF1 Weir and OF2 Weir), shown in Figure 4.8.

Additional surface water monitoring points have been established to monitor surface water run-off from the final capping works and the haul road running through the site. New lagoons (B, D and E) were constructed as part of the designed Sustainable Urban Drainage System. All of the new monitoring points are shown in Figure 4.8. The lagoons and drainage swales have been designed to run dry and are not expected to have flowing water in them all year round. Data loggers have been installed at all seven locations to allow flow data to be recorded.

4.3.1 River and Surface Water Quality

River water was collected from nine locations, including two locations off-site along the River Irt, between April 2024 and March 2025. Six of these locations are sampled on a quarterly basis with an annual sample collected from the three remaining locations, as shown in Figure 4.8.

Five surface water land drains and six off-site surface water accumulations are also sampled. Eight of the surface water locations are sampled on a quarterly basis and three on an annual basis.

A further sample point is used to monitor surface water in the drainage swale immediately downstream of the P29 investigation area. Prior to the construction of the drainage swale, TNT breakdown products were identified under the floor slab of the P29 ROF building. The area has been bunded, pending remediation, and bypassed with a temporary drainage system. Surface water monitoring in the swale immediately downstream of this area is undertaken to identify any contaminants leaching into the drainage swale and allowing us to mitigate any immediate risks ahead of remedial works.

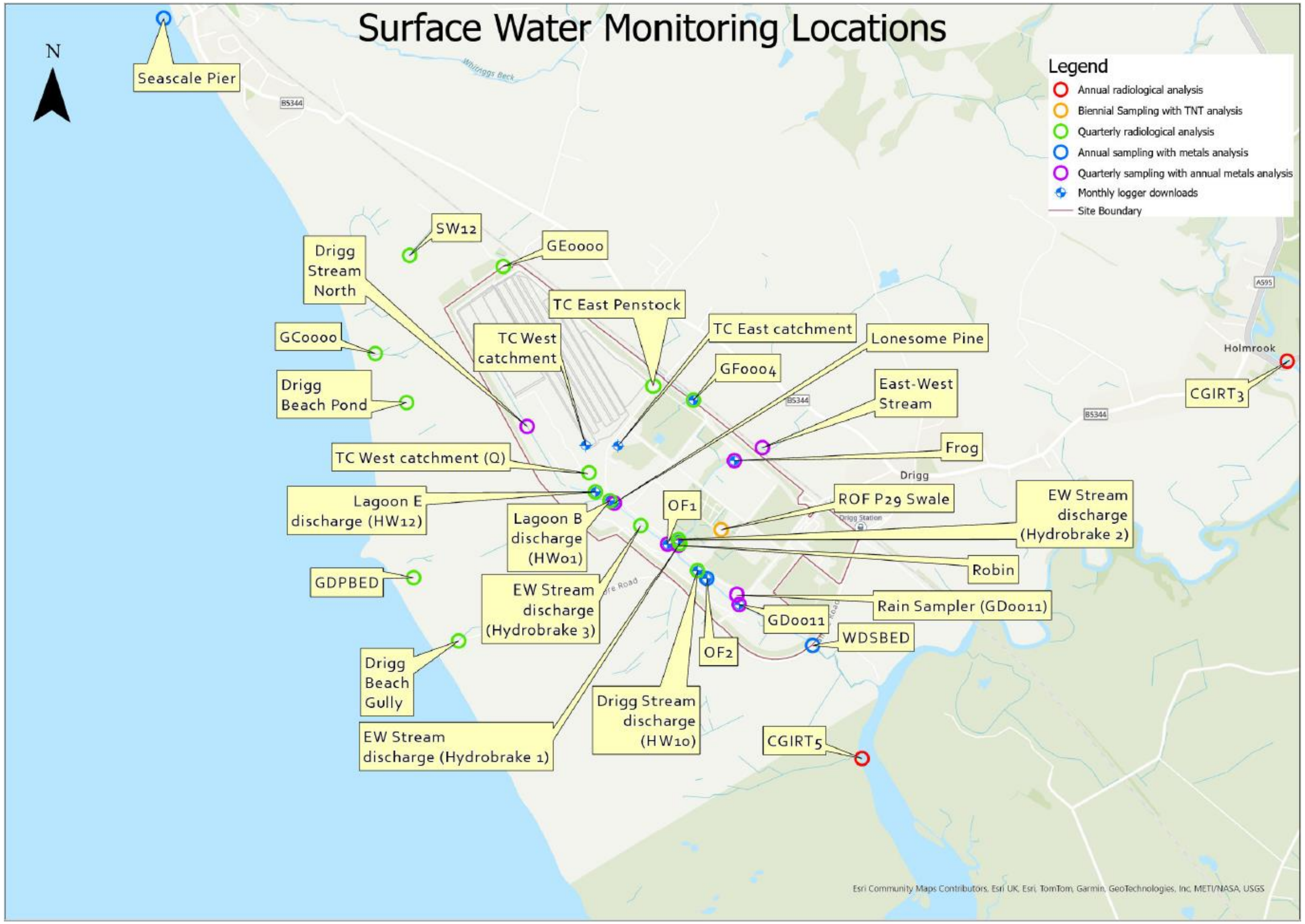


Figure 4.8: Surface Water Monitoring Locations [76]

Each of the samples collected throughout the monitoring year are analysed for a standard radiological suite and a standard non-radiological suite, biological oxygen demand (BOD) and total suspended solids (TSS) analysis.

During 2024 to 2025, twelve quality samples were submitted for a suite of major ions, metals and metalloid analysis in order to increase the size of the baseline dataset for the assessment of the potential impact from the historical ROF infrastructure and operational practices. The objective of these measurements is to identify any site-derived contamination of river or surface waters. The samples are also characterised in the field for specific conductance, pH and temperature.

4.4 Gas Monitoring

Gas monitoring involves the measurement of gas volume, flow rate, composition and migration from any gas generating sources on or around the LLWR. Landfill and radioactive gases are generated from the degradation of and releases from the wastes. There are other local sources, such as the neighbouring inert Cumbria County Council landfill site. The gas monitoring programme at the LLWR is primarily designed to assess the rate of production and migration of these gases to locations where there could be an impact on human health.

Landfill gas

The monitoring programme for landfill gas has been designed to be proportionate to the risk from landfill gas build-up in the trenches and potential migration away from them. Potential gas migration pathways have been evaluated as part of the programme design to ensure that monitoring points are correctly located to intercept them.

The LLWR is not a domestic waste landfill. The waste accepted for disposal has a much lower percentage of putrescible, cellulosic and combustible material than wastes at a typical landfill site. The potential for generation of significant volumes of landfill gas from the trenches and the vaults is, therefore, considered to be low and this is confirmed by monitoring and modelling of gas generation [6]. Probe holes were driven into the trenches to allow gas venting and sampling as part of the construction of the interim cap. The majority of the probe holes are open to allow venting, whilst some have gas caps on to allow gas sampling and pressure measurements. No gas monitoring infrastructure is currently installed in the vaults as no cap is present. These areas vent directly to the atmosphere. The current monitoring programme for landfill gas, therefore, principally monitors gas generation and migration from the trenches. Building monitoring in the southern area of the site is also completed as a precaution against the potential migration of landfill gas from the former Cumbria County Council landfill site that borders the site.

Each quarter, the measured methane concentrations and flow rates at each of the venting and sealed probe holes (Figure 4.9) are used to assess the extent of landfill gas generation across the trench disposal area [37].

Landfill gas migration is monitored at eighteen locations (perimeter wells) around the perimeter of the LLWR and in eighteen on-site buildings. An annual walkover survey of the trench cap and the perimeter of the trench disposal area is also carried out, measuring gas concentrations at ground level, to assess migration of gas through the interim trench cap.

Ongoing construction works to replace the interim membrane over the southern part of the trenches will require substantial changes to monitoring infrastructure including the extension of existing probe holes and the installation of sacrificial loggers. There will be limited access to areas of the cap during construction works. Whilst all effort will be made, it may not be possible to carry out quarterly gas monitoring at all probe holes throughout the construction works.

Carbon-14-bearing gases

Seven sealed probe hole locations across the trench cap are used to monitor for carbon-14-bearing gases. The seven locations were sampled to measure the concentration of carbon-14 present in CO_2 and organic species (e.g. CH_4). This analysis is undertaken annually.

Radon and thoron

A comprehensive programme of radon analysis is undertaken across the site, using passive alpha track detectors to identify the presence of radon gas (Figure 4.10). This comprises monitoring of the trench cap, vaults and operational areas, the site perimeter and buildings to assess the potential risk to human health.

In conjunction with the analyses of carbon-14-bearing gases, the same seven sealed probe hole locations were used to obtain in-situ radon and thoron measurements using passive alpha track detectors over a period of three days.

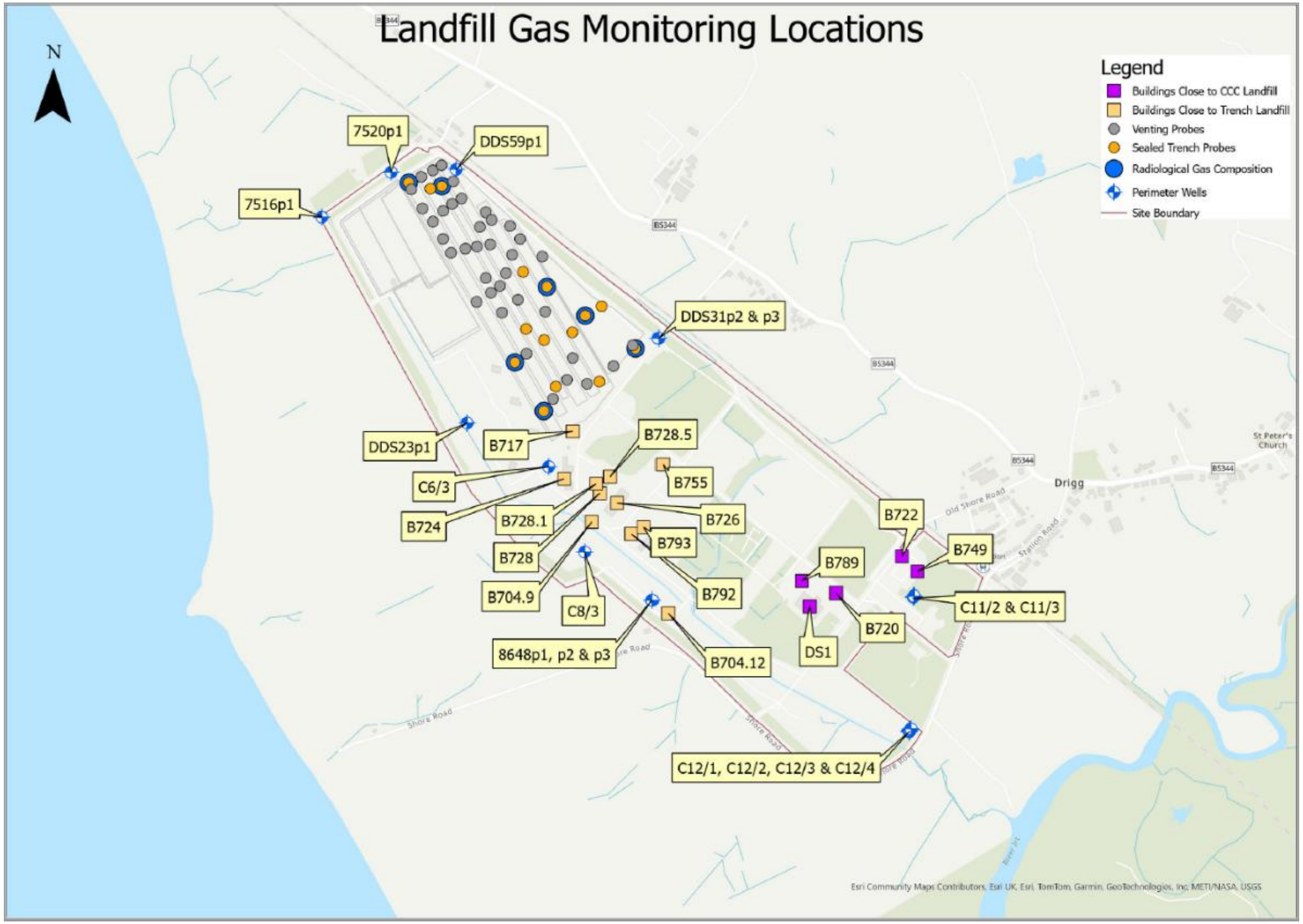


Figure 4.9: Landfill Gas Monitoring Locations [76]

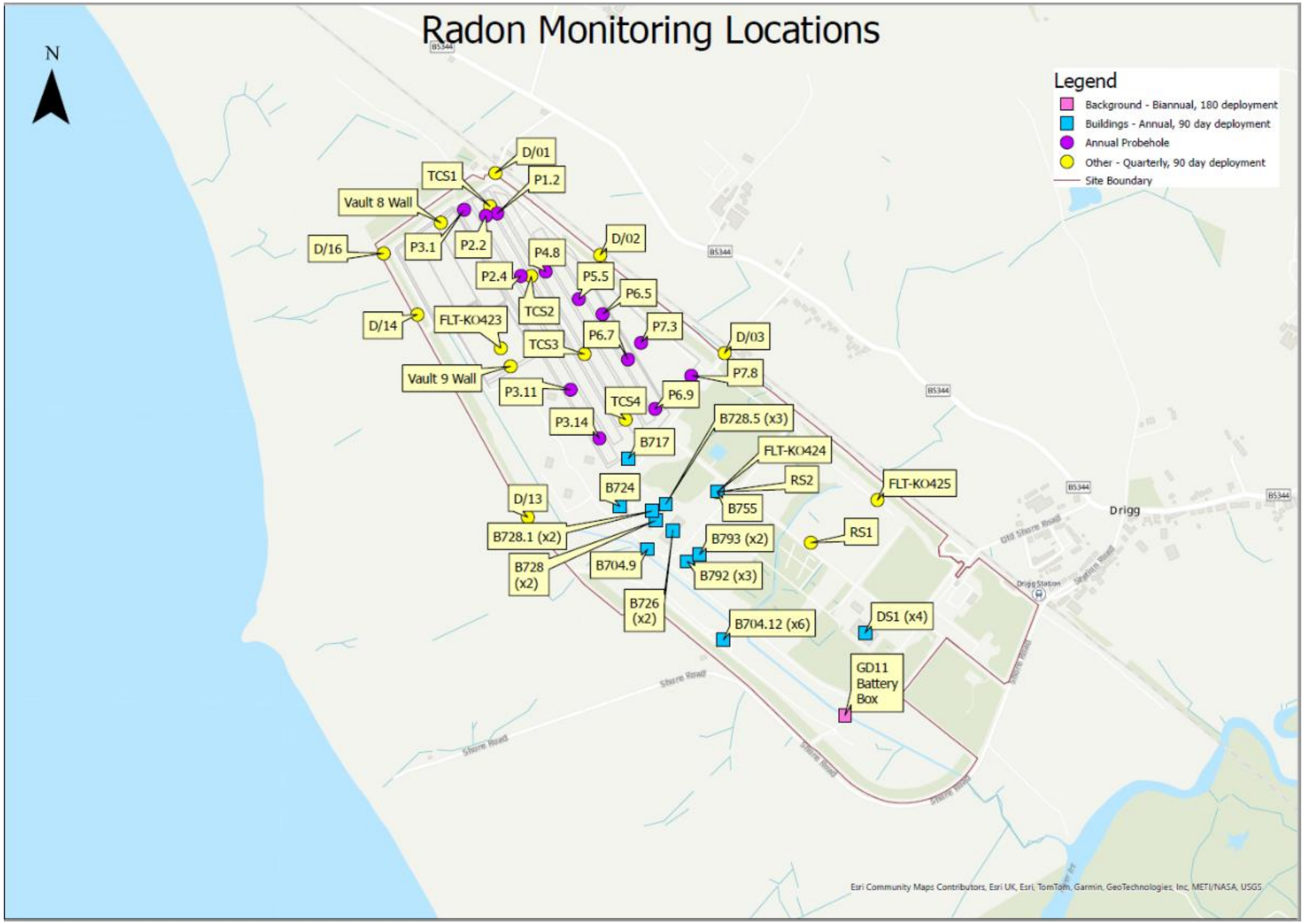


Figure 4.10: Radon Monitoring Locations [76]

4.5 Reassurance Monitoring

Monitoring is undertaken to provide reassurance that the site is not having an undue impact on its surroundings. Reassurance monitoring assesses the potential for contamination in the area around the LLWR, which might arise from aerial deposition and the migration of contaminated sediments.

Grass and soil

A significant baseline for radiological species in grass has been built up from four locations around the perimeter of the LLWR site and one location on site over 16 years. Previous results have detected negligible contaminant concentrations and a very low likelihood of a pathway to receptors being realised.

With the closure of the Magazine Recovery Facilities in 2019, site aerial emission sources have reduced from six locations to two locations with a corresponding reduction in total aerial activity. Following review, monitoring of radiological species in grass has been reduced from a yearly to a triennial frequency

Stream sediment

Prior to 1991, leachate from the disposal area was discharged directly into the Drigg Stream. As such, radioactive contamination of the sediments in the stream is known to have occurred, and this contamination remains present in the deeper sediment deposits in the Drigg Stream. Samples of recently deposited sediment are collected from three locations along the length of the Drigg Stream on a quarterly basis (Lonesome Pine Weir, GD0011 Weir and WDSBED) (Figure 4.11). This sampling is undertaken to identify if historical contamination is being liberated, migrating downstream and potentially exiting the site boundary.

Milk

One sample of milk from a farm with substantial pasture within four kilometres of the site is analysed annually. The sample is analysed for the standard radiological suite.

Ambient air sampling

Ambient air sampling with a high-volume air sampler is undertaken at a location close to the main gate (UDRIGG), see Figure 4.11. Samples are collected each month and analysed for total alpha, total beta, tritium and a gamma scan. Beryllium-7, caesium-137, potassium-40 and all other detected gamma emitting radionuclides are reported as part of the gamma scan. An annual sample is also collected for additional radionuclide analysis: americium-241, plutonium alpha, plutonium-241 and uranium alpha.

Aerial discharge monitoring

The Permit requires the monitoring of gaseous discharges from the active building ventilation discharge stacks. Prior to discharge, all gaseous discharges pass through a double HEPA filtration system. Assessment of the results is presented in the '*Liquid and Gaseous Effluent*

Discharge' report [79]. Two active ventilation systems remain operational on site, the Drum Store stack and B755 Drigg Grouting Facility stack (Figure 4.4). For the last three years, the grouting of containers has transitioned to grouting in batches, when required, rather than continuous operation. This is due to the reduced numbers of LLW waste containers the site receives annually, as a result of the successful implementation of waste treatment and diversion. The B755 stack system has remained in operation throughout the period.

Dose rate monitoring

Dose rate monitoring points are selected to measure the external radiation dose of the site's radioactive inventory to identified receptors.

District gamma dose rate monitoring is carried out monthly at Drigg Beach, quarterly at two locations near the confluence of Drigg Stream and the River Irt, and annually at four locations around Drigg and Holmrook. The locations are shown in Figure 4.13.

Passive monitoring is carried out at 29 locations using thermoluminescent dosimeters replaced at quarterly intervals. Nineteen dosimeters are located around the site perimeter and ten are located in operational areas on site (Figure 4.12). The dosimeters are positioned to measure gamma radiation present in the surrounding environment and are exchanged at quarterly intervals. An additional dosimeter is located off-site to provide background measurement.

The annual direct radiation dose uses dose rate data collected from the dosimeters deployed around the site perimeter fence and is calculated for three different groups of members of the public to assess the potential direct radiation dose for the most exposed group. The three resident groups are:

- itinerant members of the public adjacent to the site perimeter fence, such as dog walkers;
- coal yard employees working alongside the north-western side of the site perimeter opposite Vault 8. It is noted that the coal yard has recently ceased operation but is currently retained to assess the potential impact to different groups;
- Local residents living adjacent to the site perimeter.

Health physics contamination monitoring

Radioactive contamination monitoring surveys were carried out by suitably qualified health physics monitors at off-site locations to confirm there has been no impact through the deposition of radioactive materials from the LLWR.

District beta and gamma dose contamination monitoring is carried out annually at four locations shown in Figure 4.13. The monitoring is carried out at a further four locations near the site perimeter on a biannual frequency. Surveys are undertaken by direct probe measurement just above the surface of the ground across the length of the survey area.

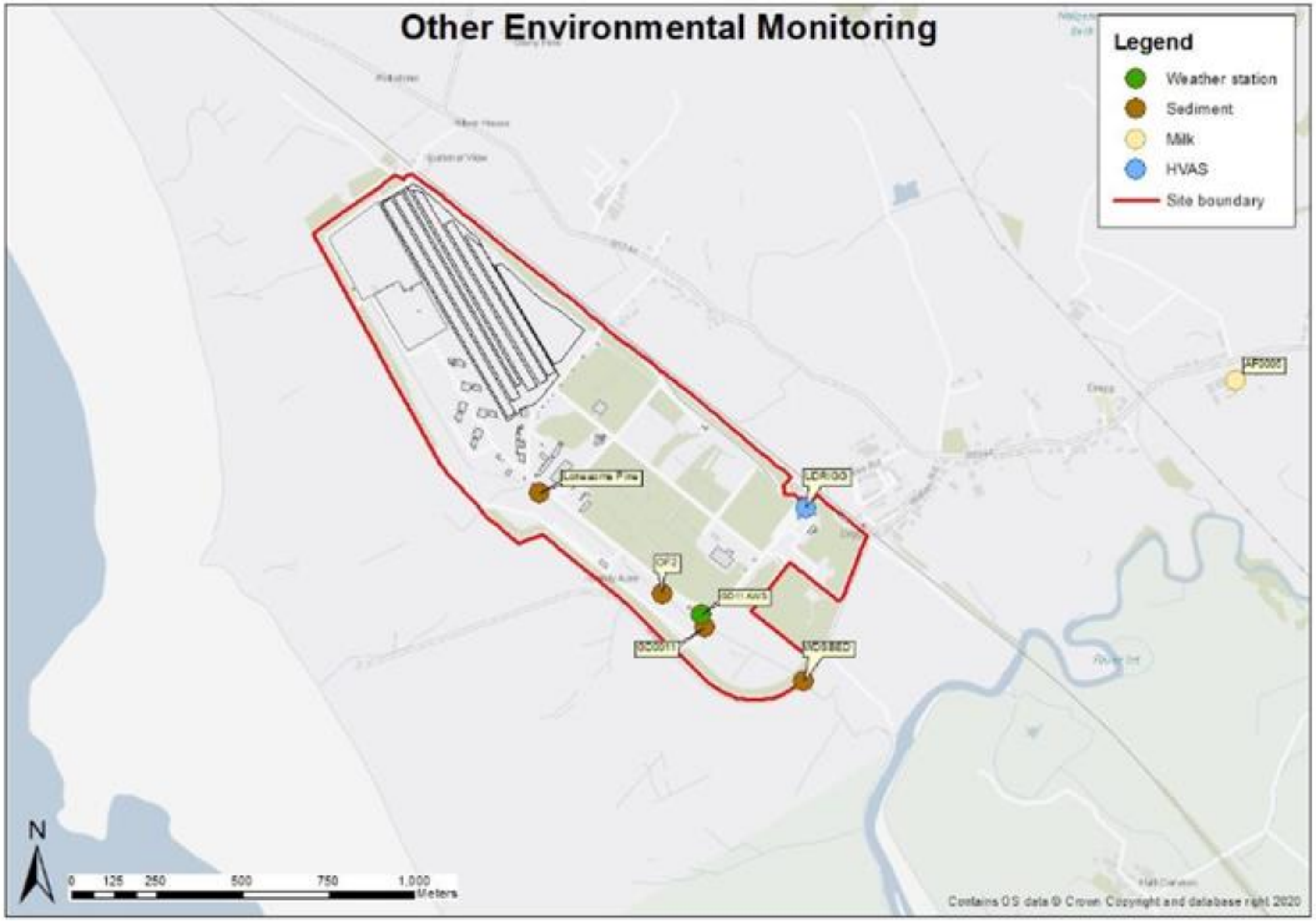


Figure 4.11: Other Environmental Monitoring Locations [76]

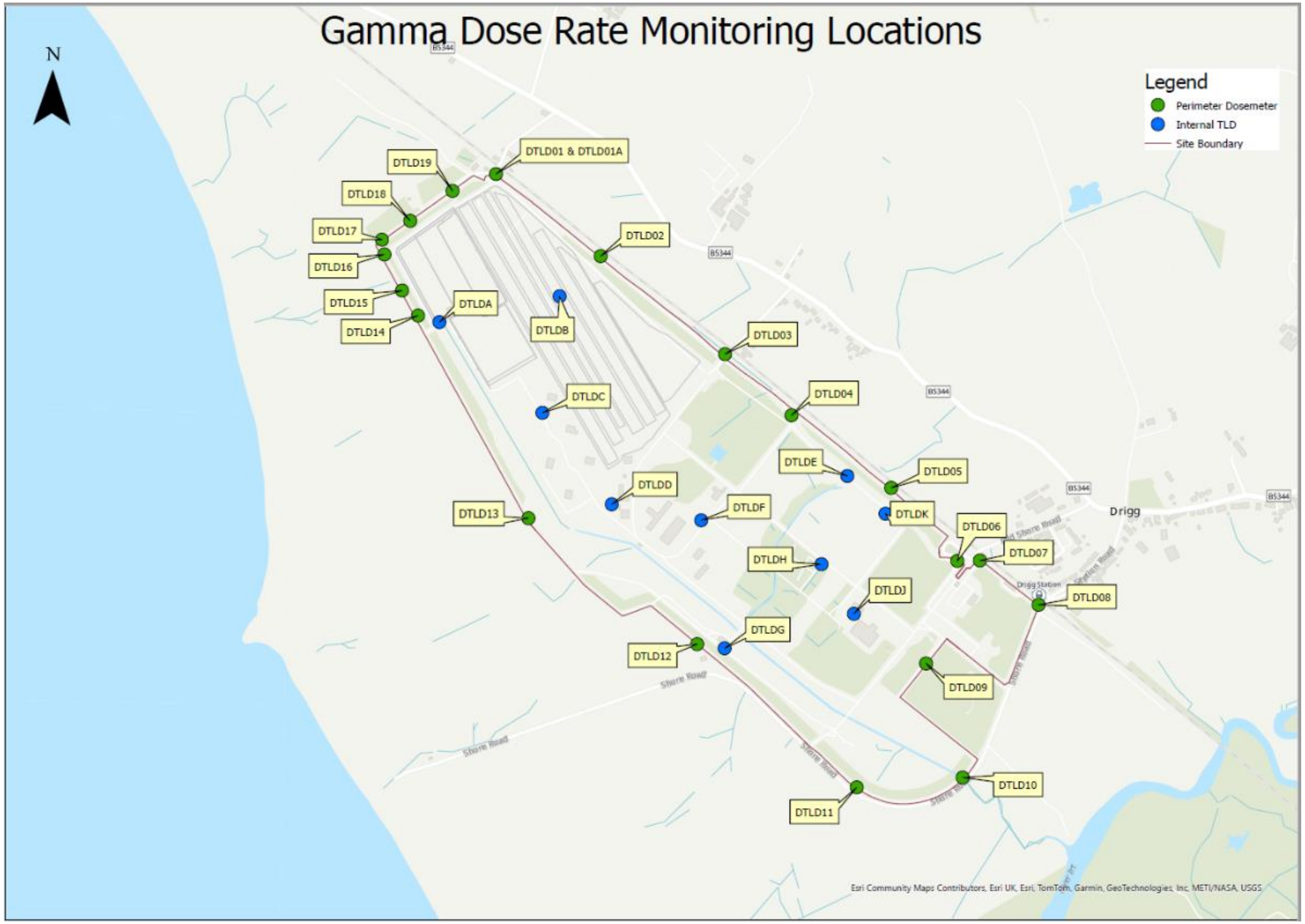


Figure 4.12: Gamma Dose Monitoring Locations [76]

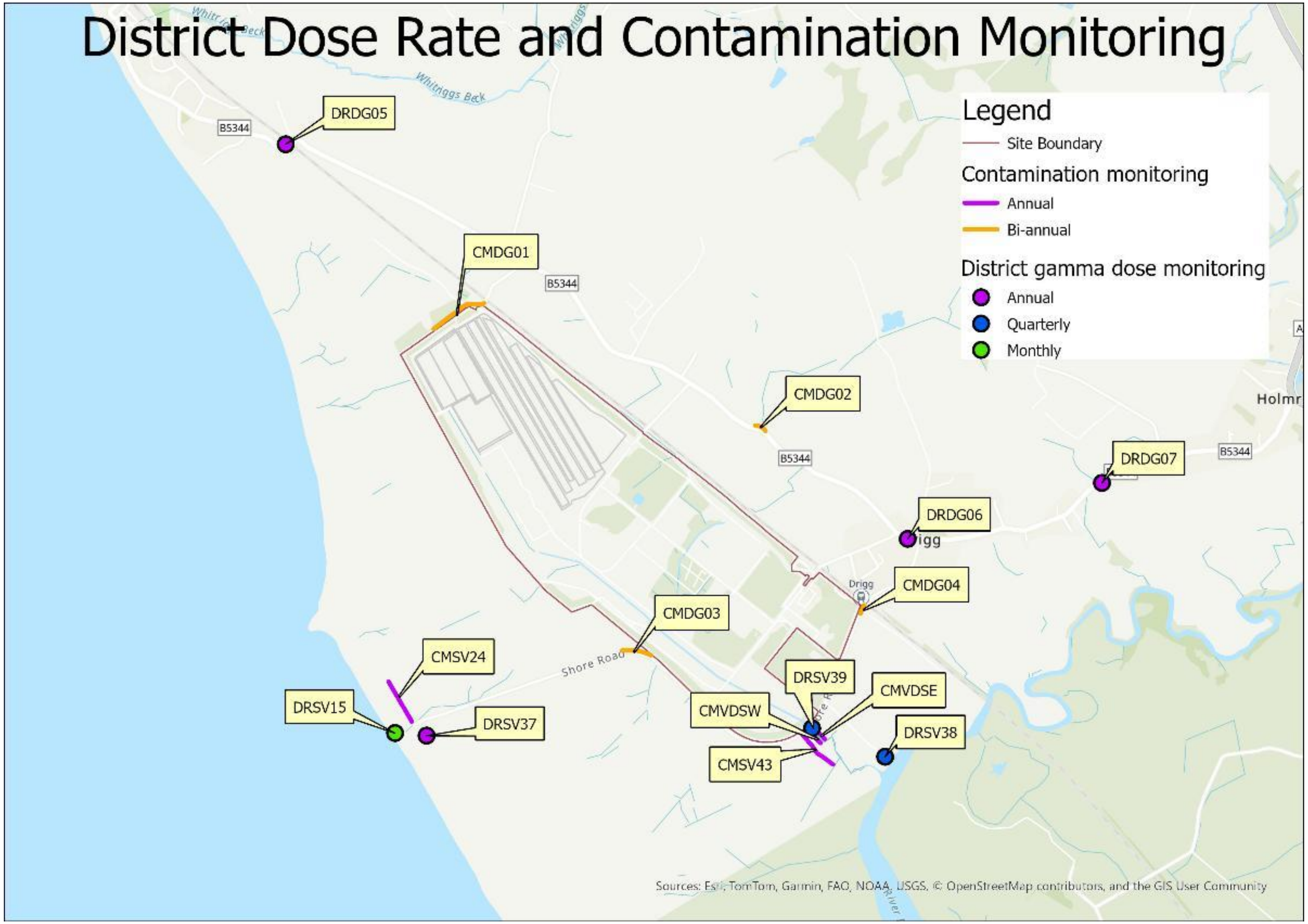


Figure 4.13: District Dose Rate and Contamination Monitoring Locations [76]

4.6 Additional Monitoring

Weather data

Previously, an automatic weather station (CAP2) located on the trench cap was the primary weather station on site. However, in April 2023 this weather station was removed from the trench cap due to the beginning of the installation of herringbone drainage as part of the disposal area capping works. The secondary weather station, located near GD0011 weir, has now become the primary on-site weather station, as shown in Figure 4.11.

The weather station records rainfall, relative humidity, wind direction and speed (both gusts and fifteen-minute averages), net radiation, clear sky radiation, solar radiation and temperature. These data are used to support the calculation of evapotranspiration rates from the trench cap and to provide general baseline site information.

Two automatic data loggers have been installed at the LLWR to record barometric pressure and air temperature. In addition to direct usage, the pressure readings are to be utilised in conjunction with other automatic data loggers to facilitate compensation of those readings in accordance with the manufacturer’s instructions.

Sewage effluent discharges

The LLWR is permitted to discharge treated sewage from two sewage treatment plants (STP1 and STP2). We are required to correctly manage and maintain the plants so that stated discharge volumes are not exceeded, and no visible oil or grease is present. A third sewage treatment plant (STP3) was installed in the site reception area during October 2017 and a fourth (STP4), adjacent to B789, during July 2020 (Figure 4.4). The discharges from these plants are less than 5 m^3 per day and therefore do not require a permit. The requirements for the operation of these plants are consistent with those for the operation of STP1 and STP2 and are managed in the same way. The results of the monitoring and an assessment of the results are presented annually in the '*Liquid and Gaseous Effluent Discharge Report*' [79].

Noise

Noise level measurements have been undertaken at the LLWR, principally to assess the noise levels generated from cap construction activities in order to identify and mitigate against noise. During 2024/25, installation of the replacement trench cap membrane, minor construction activities, and deliveries of stone for profiling purposes were the main noise generating activities. Noise monitoring was conducted quarterly at seven locations around the perimeter of the site during 2024/25 as well as a silent hours survey. The locations have been chosen to target the nearest sensitive receptors (local residents), or an alternative agreed location, in accordance with BS7445-1:2003 and BS4142:2014. All seven monitoring locations (as shown in Figure 4.14) will continue to be monitored beyond the current construction phase.

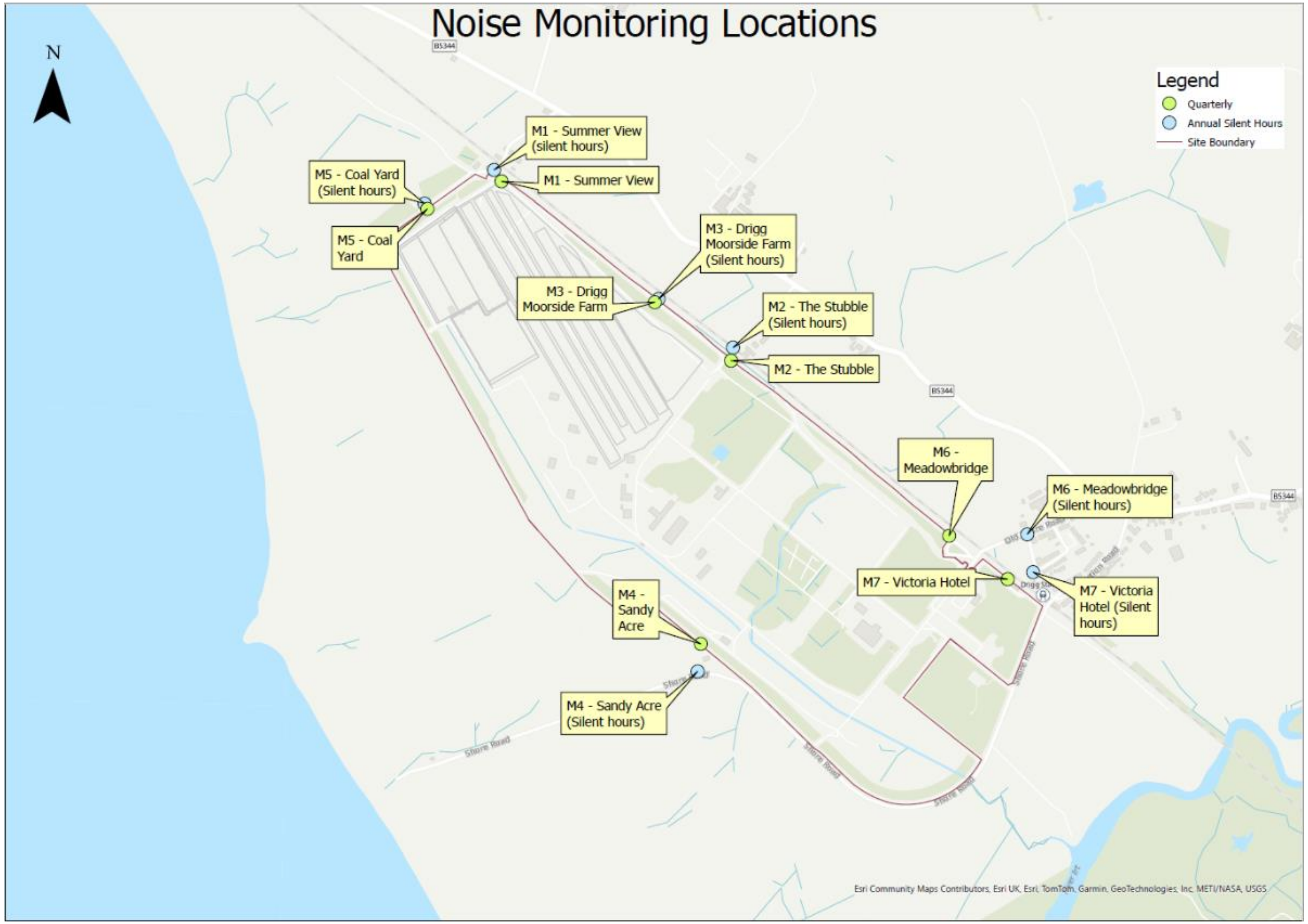


Figure 4.14: Noise Monitoring Locations [76]

Coastal surveys

Since 2012, the LLWR has undertaken an annual coastal monitoring survey [80] from St Bees Head to the Drigg Spit, within coastal monitoring Cell 11 [81]. The survey entails a systematic walk-over of the coastline, following the winter period, to observe and record evidence of coastline change and the effects of winter storms. Fixed point photography is carried out at 32 specified locations. The locations have been selected to document variation in beach height against fixed features, such as groynes or sea walls, to provide a basic indicator of beach behaviour. During each survey, additional points of interest are also recorded, if observed. The results of each survey are assessed alongside an annual review of weather data to identify the number, frequency and impact of storms. A review of monitoring programmes undertaken by other organisations within the coastal monitoring cell is also incorporated into each survey report to help build an understanding of the changing behaviour of the coastline.

Localised erosion rates of approximately 0.1 m y^{-1} have been occurring around the Barn Scar section of the coast. Parts of this area were excavated and reinstated during installation of the Marine Pipeline. Additional regular monitoring, with drone photogrammetry, has been instigated along this section of the coast to help identify when the leachate line infrastructure is likely to be impacted.

Trench cap visual and topographic surveys

Visual walkover surveys of the trench cap were replaced with Unmanned Aerial Vehicle (UAV) surveys in 2018. These surveys are carried out to identify whether any collapsing ground, settlement or holes in the interim trench cap are present. They are also used to identify areas requiring vegetation management such as scrub clearance or changes to land use that may affect evapotranspiration calculations.

Vault 8 container condition surveys

There is a requirement for visual checks of the structural integrity of the waste containers within Vault 8 and Vault 9 to be completed by the NWS engineering department. This information is utilised in the '*Disposal Area Performance*' report [39] produced annually.

Colloid monitoring

Colloids are particles between 1 nm and 1 μm in diameter suspended in aqueous solution. They can transport radionuclides either as intrinsic colloids (radioelement aggregates) or pseudo-colloids (radionuclides sorbed onto other particles like clays or microbes) and are a key consideration in the ESC. A colloid monitoring programme was commissioned in 2020 following a review of best practice techniques by an independent expert [82]. Groundwater samples were collected from five probe holes (7536p1, 8420p1, 8646p1, 8670p1, and Fp1) chosen for their higher radiological contamination levels. Two samples per location were filtered: one through a 1.0 μm filter (to retain colloids) and one through an ultrafiltration cartridge (to remove colloids). Both were analysed for standard radiological parameters to assess whether colloids contributed to contaminant transport. Initial results showed no significant difference in activity concentrations between filtered and unfiltered samples, suggesting limited colloid-associated transport. Monitoring is currently biannual, but the decommissioning of the probe holes will impact future sampling coverage.

Complexant monitoring

Complexing agents (complexants) are species that can bind to a metal ion with one or more bonds to form a complex. Complexants can significantly increase the solubility of radionuclides and decrease their ability to sorb onto solid matrices within the repository near field. They may originate from waste or be generated chemically in the near field. Their presence in waste can affect contaminant transport and repository performance, making them a key concern in the ESC.

We have concluded that the amino-polycarboxylic acid complexants, such as ethylene-diamine tetra-acetic acid (EDTA), diethylene-triamine penta-acetic acid (DTPA) and nitrilo tri-acetic acid (NTA), have the greatest potential to adversely impact repository performance because they commonly occur in waste, are able to form stable complexes with a range of contaminants and are persistent in the repository environment. Of these species, EDTA is the most commonly occurring, and EDTA is taken to be representative of the broader class of amino-polycarboxylic acid complexants in ESC assessments. Monitoring data have been used to confirm the presence of EDTA in trench leachate and to underpin the reference concentration of EDTA applied in our assessment of the environmental impact of the trenches [83].

Initial sampling from five trench cap probe holes was undertaken in 2012 and sample analysis was carried out at Loughborough University for the presence of EDTA [84]. EDTA was detected in three of the five samples collected. The 2012 results were used to determine the trench reference concentration applied in the assessment models [85]that underpinned our 2013 application to vary the Permit to allow the disposal of organic complexants in waste under appropriate controls [86]. Since 2012, the EDTA analysis technique has been further developed through collaboration with the University of Manchester. A study was carried out in 2018 as part of a PhD project, which sought to develop a robust analytical procedure for quantification of amino-polycarboxylic acids in environmental and other complex matrices [87, 88].

In 2021, we issued the Complexants Monitoring Strategy, which sets out our strategy for the monitoring of organic complexants present in leachate arising from the trenches at the LLWR [89]. The strategy included sampling from probe holes and trench drainage points, with a preference for probe holes due to them being more representative of in-situ conditions. Sample preservation measures, such as acidification and control of redox potential, were proposed to prevent biodegradation. Annual sampling campaigns were proposed, with the potential to extend the monitoring scope to other amino-polycarboxylic acids as analytical methods develop.

During 2020/21, a route was established for the commercial analysis of future samples. Further works were undertaken in 2021 to identify potential sampling points from the trench cap probe holes. Locations with >0.5 m of leachate present were pumped out in order to assess the recharge rate of the leachate and identify if the location would be suitable for further sampling. From this initial investigation, fifteen trench cap probe locations were identified and samples from these locations were collected and analysed for EDTA during March 2022 and September 2024. Attempts to sample and analyse for complexants in other years have faced significant disruption and delay with the commercial laboratory being unable to complete the analysis within the valid sampling window (the Complexants Monitoring Strategy [89] states that sampling and analysis should be conducted in the summer months when rainfall is lowest). We intend to continue sampling on an annual basis once service reliability issues have been resolved.

The results of our recent analyses of trench leachate are consistent with those undertaken previously and we continue to use a trench reference concentration of 1 10^{-7} M for EDTA in ESC assessment calculations.

5 Results from the Monitoring Programme

This subsection presents an overview of the key results from the integrated monitoring programme and discusses their implications. This focuses on four aspects:

- contamination of ground and surface waters by non-radiological contaminants;
- contamination of ground and surface waters by radioactive contaminants;
- the performance of the engineered barriers;
- authorised discharges.

This is not a comprehensive overview of the monitoring programme results because some aspects are examined further in other ESC documents. For example, the use of coastal monitoring data is described in the '*Site Evolution*' report [8]. The results from the environmental monitoring programme from April 2024 to March 2025 are presented more fully in the annual monitoring report [37].

5.1 Contamination of Groundwater and Surface Waters by Non-radiological Contaminants

A review of non-radiological data for surface water, groundwaters and leachate was undertaken for the 2011 ESC [90]. The review found that the main exceedances of the relevant standards arise for ammonium, arsenic, iron, manganese, nickel, nitrate, nitrite and sulphide. It is likely that these substances are present in the groundwater (and surface water) as a result of natural processes, with the exception of nitrate, which is present as a result of the use of artificial fertilisers in the area up-gradient of the site. Contamination does not appear to be localised around the LLWR. On this basis, it was concluded that activities at the LLWR have not resulted in significant non-radiological contamination of groundwater beneath the site, or surface water passing through the site.

Non-radiological data have since continued to be collected. As noted in Subsection 4.2, the range of non-radiological analytes has increased since 2017 and has been used to update the hydrogeochemical understanding of the LLWR site [29]. These have been used to inform the MALs used to assess the non-radiological impact of the LLWR site operations on groundwater. The updated hydrogeochemical understanding concurred with earlier work in 2010 [90] that showed little effect of non-radioactive contaminants on the groundwater composition and that the following conclusions were retained:

- Most contaminant substances are present in groundwater, surface water and leachate at concentrations below their water quality standards.
- There is limited evidence of contamination of groundwater, surface water and leachate as a result of historic or current activities at the site; contamination that is

present is generally at low concentrations, with few exceedances of water quality standards.

- The organic contamination that is present, which is principally in the form of hydrocarbons, toluene, phenol and explosives residues does not appear to be related to the waste disposal operations at the LLWR but is likely to be related either to the former use of the site or to natural processes.

However, it did note that in cluster borehole C6 (close to the south-west corner of the trenches) there is a clear correlation between the chloride and tritium concentrations, consistent with a common source of contamination from the trench disposal wastes.

Groundwater

While there are no historical groundwater quality data from the period before disposal operations began in 1959, current groundwater quality data may be compared with baseline values derived during an extensive review of non-radiological water quality entering the site reported in 2026 [74]. Such comparison reveals that groundwater quality in the periods 2016 to 2020 and 2021 to 2025 is broadly consistent with that reported in the 2017 Hydrogeological Risk Assessment [91]. This suggests no evolving risk posed to groundwaters due to release of non-radioactive contaminants from the site. It also suggests that there is no need to increase the frequency of the non-radiological aspect of the triennial monitoring programme. These data indicate that there were MAL exceedances for ammoniacal nitrogen, arsenic, barium, cobalt, copper, cyanide, iron, lead, magnesium, nickel, phenol index, vanadium and zinc. Ammoniacal nitrogen, arsenic and barium were the contaminants with the greatest number of MAL exceedances. Ammoniacal nitrogen is present in the groundwater because of local agricultural practices. Monitoring and assessment evidence shows that LLWR operations have not resulted in significant non-radiological contamination of groundwater [15, 75]. Where non-radiological substances are detected, concentrations are generally low, consistent with natural background levels, and not localised around the LLWR site.

Surface water

River water quality samples are collected at various locations as described in Subsection 4.3, principally at river water sampling points or the outfalls into the Drigg Stream and East-West Stream. In the third year of the triennial cycle, samples are analysed for an enhanced suite of non-radiological contaminants. 2025 was the most recent such enhanced sampling year, the previous being 2022. Metals and non-metals were monitored on an annual basis between 2019 and 2023 in all river water samples. The results are consistent with the baseline river water quality values derived. This suggests no evolving risk posed to river waters due to release of non-radioactive contaminants from the site. It also supports the view that there is no need to increase the frequency of the non-radiological aspect of the triennial monitoring programme.

There were six (1.9%) river water baseline exceedances for non-radiological determinands in the period 2016 to 2020 and sixteen (3.2%) in 2021 to 2025. Six of the exceedances observed in the 2021 to 2025 period are for sulphate as SO_4, which was not included in the analysis suite between 2016 to 2020. Examination of trended data did not reveal any adverse trends at the relevant locations.

No contaminants consistently exceeded the river water baseline concentrations and the concentrations observed do not indicate an impact of site operations on the quality of on-site streams.

BOD and TSS analysis are routinely undertaken on each of the river water and surface water samples collected on a quarterly or annual basis. Elevated TSS results principally occurred during periods of low rainfall when the levels at the respective water bodies have been low, and sediment has been mobilised during sampling. Occasional spikes in BOD have been recorded, but no sustained elevated concentrations have been recorded that would indicate a change in river or surface water chemistry on or surrounding the site and the results observed remain consistent with previous years. Short term TSS and BOD spikes have also been recorded during storm events.

5.2 Contamination of Groundwater by Radioactive Contaminants

As noted in Subsection 4.2 all groundwater samples are analysed for a standard radiological suite comprising total alpha, total beta, tritium and a gamma scan. Actinium-228, americium-241, beryllium-7, cobalt-60, caesium-137, potassium-40, radium-226, ruthenium-106, uranium-235 and all other detected gamma emitting radionuclides are reported as part of the gamma scan.

Tritium in groundwater

Tritium, as tritiated water, is a useful tracer in groundwater as it is transported at the flow velocity. Identification of tritium at monitoring locations indicates the presence of a migration pathway for contaminants in the groundwater underlying the site. It is noted that the trench inventory of tritium is not fully characterised. While discrete disposals to Trenches 3 and 6 have been identified, other trenches are also likely to contain tritium-bearing waste. However, the exact location, form, and containment status of these disposals remain unclear. This makes it difficult to pinpoint the origin of observed tritium. Additionally, degradation of waste packaging – such as vials and drums – may have resulted in episodic releases. These releases may be accelerated by physical disturbances, such as cap loading by construction vehicles during drainage repairs.

Tritium activity levels in the Medium and Deep Groundwater depth intervals are higher than those in the Upper and Intermediate Groundwater depth intervals, see Figure 5.1 to Figure 5.4.

The tritium activity levels in the Regional and Upper Groundwater continue to indicate that there is limited lateral migration of tritium through the Upper Groundwater, with a predominantly vertical movement to the Regional Groundwater. Once in the Regional

Groundwater, the tritium predominantly migrates laterally toward the south-west, as is consistent with the hydrogeological conceptual model [24].

During 2024/25, the number of groundwater wells where elevated levels of tritium are recorded has remained consistent with previous observations. These wells are located underlying, immediately adjacent to, or downstream of the disposal area.

Although the tritium activity concentrations in groundwater are generally consistent with previous observations, there have been two wells that have shown upward trends in tritium activity. Both are off site to the west of the site. The levels are relatively low but indicate a change in contaminant migration in the area, which will continue to be monitored.

Locally, tritium concentrations may be high enough to exceed the LLWRAS, should they be extracted for domestic use. The resultant plume of tritium contamination in the groundwater is restricted to the local environment immediately to the west of the site, underlying the adjacent SSSI, with LLWRAS exceedances observed at a small number of locations. This is indicated by locations highlighted in orange and red on Figure 5.1 to Figure 5.4. These concentrations are the result of leaching from the trench disposal area reflecting the relatively high mobility of tritium and the elevated tritium levels found in trench leachate. Concentrations at these locations are expected to decrease over the next 50 years as a result of radioactive decay and a reduction in leaching from the source. Although there may be a short-term increase in releases due to increased loading and consolidation displacing leachate, the work to replace the membrane over the southern part of the trenches and the construction of the final cap are ultimately expected to reduce the infiltration into the waste and reduce releases.

The tritium concentrations recorded are considered to be of low impact to the environment and pose no significant risk to members of the public for the following reasons:

- There are no groundwater abstractions currently undertaken between the LLWR and the coast, as shown in Figure 2.8.
- The designated SSSI is currently under a long-term (999-year) lease agreement to the NDA. This ensures that NWS has control over future development on the SSSI, including the installation of groundwater abstraction wells. It is not credible, therefore, that a well could be sunk in the near term to abstract contaminated groundwater.
- The relevant receptor when assessing protection of groundwater is therefore a marine foodstuffs consumer. Our assessment model demonstrates that doses to a marine receptor are much less than 0.01 mSv. Doses to non-human biota are calculated to be very low.
- We have also considered, for the same period, a 'what if' in which a hypothetical well is sunk between the LLWR site and the coast. Our monitoring data indicate that, for the present day, assessed doses would be around 0.18 mSv for localised regions between the site and the coast. These doses largely arise from tritium disposed of in

the trenches, with doses of around 0.01 mSv arising from C-14, which has migrated from the trenches via low dilution pathways.

- As the well is a 'what if' calculation for the near term, we do not judge it appropriate to combine the assessed groundwater impacts with those from other pathways during the PoA, even though the assessed dose exceeds, in localised regions, 0.01 mSv.

As part of our optimised Site Development Plan, we will, over the course of the PoA, implement the following engineering measures to ensure that impacts to groundwater are as low as reasonably achievable:

- remediate the interim trench cap covering the southern portion of the trenches;
- install the final cap, initially over Vault 8 and the adjacent strip of trenches and, subsequently, over the remainder of the vaults and trenches;
- extend the existing cut-off wall.

These measures will reduce the inflow of water into the trenches and hence the production of leachate and release of radionuclides to groundwater. This reduction in releases, together with the short half-life of tritium, will result in concentrations of tritium (and hence assessed doses) reducing significantly over the next few decades.

For the remainder of the PoA, there is greater uncertainty as to whether a well could be sunk. We assume, therefore, that a well could be sunk after the end of operations. We have used monitoring data to understand how contaminants move from the site to the coast and to develop groundwater models that allows us to predict future movements. We therefore use our assessment model to calculate doses for the remainder of the PoA. We calculate assessed doses from the ingestion of contaminated groundwater to be less than 0.01 mSv.

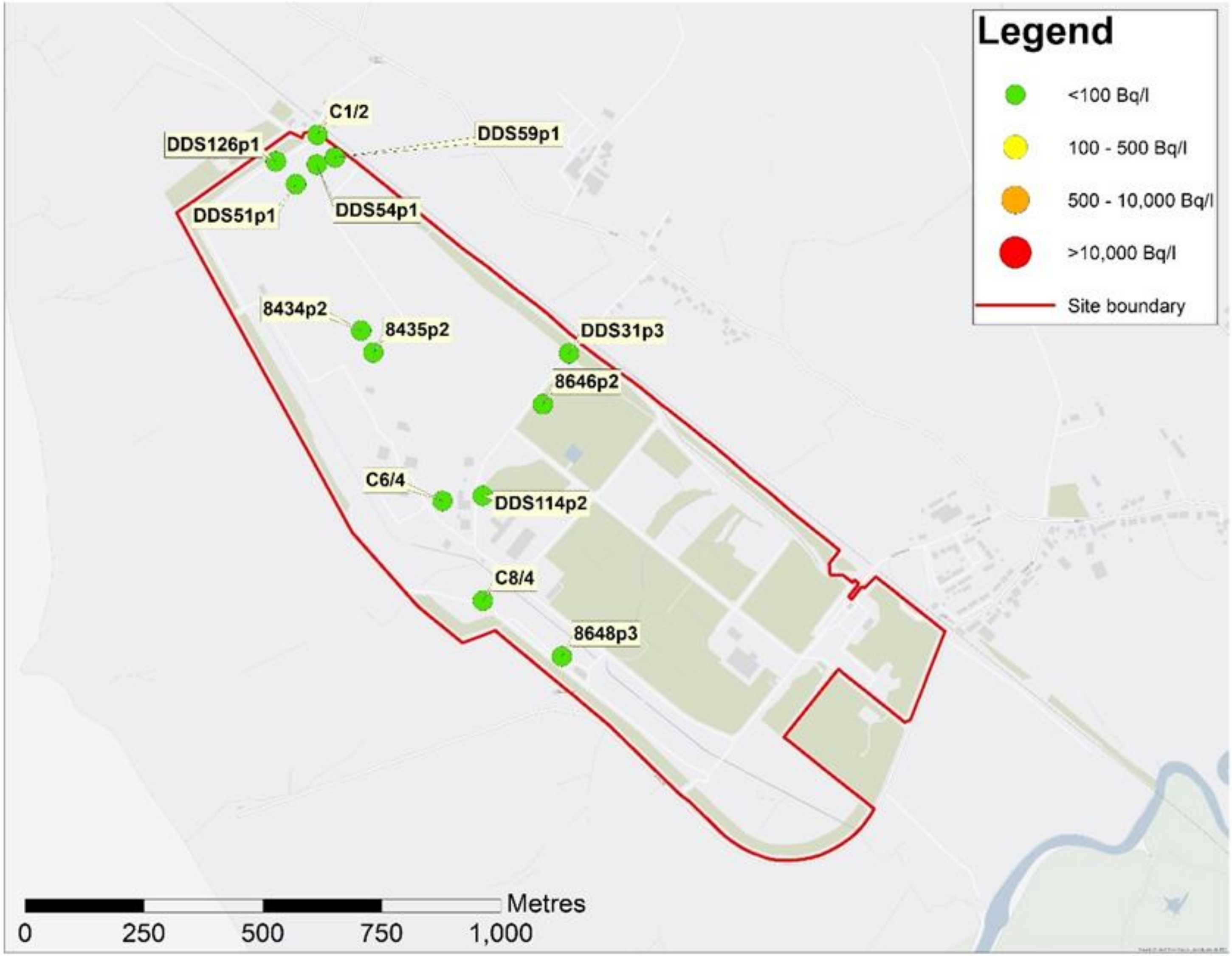


Figure 5.1: Tritium activity in Upper Groundwater 2024 to 2025 [37]

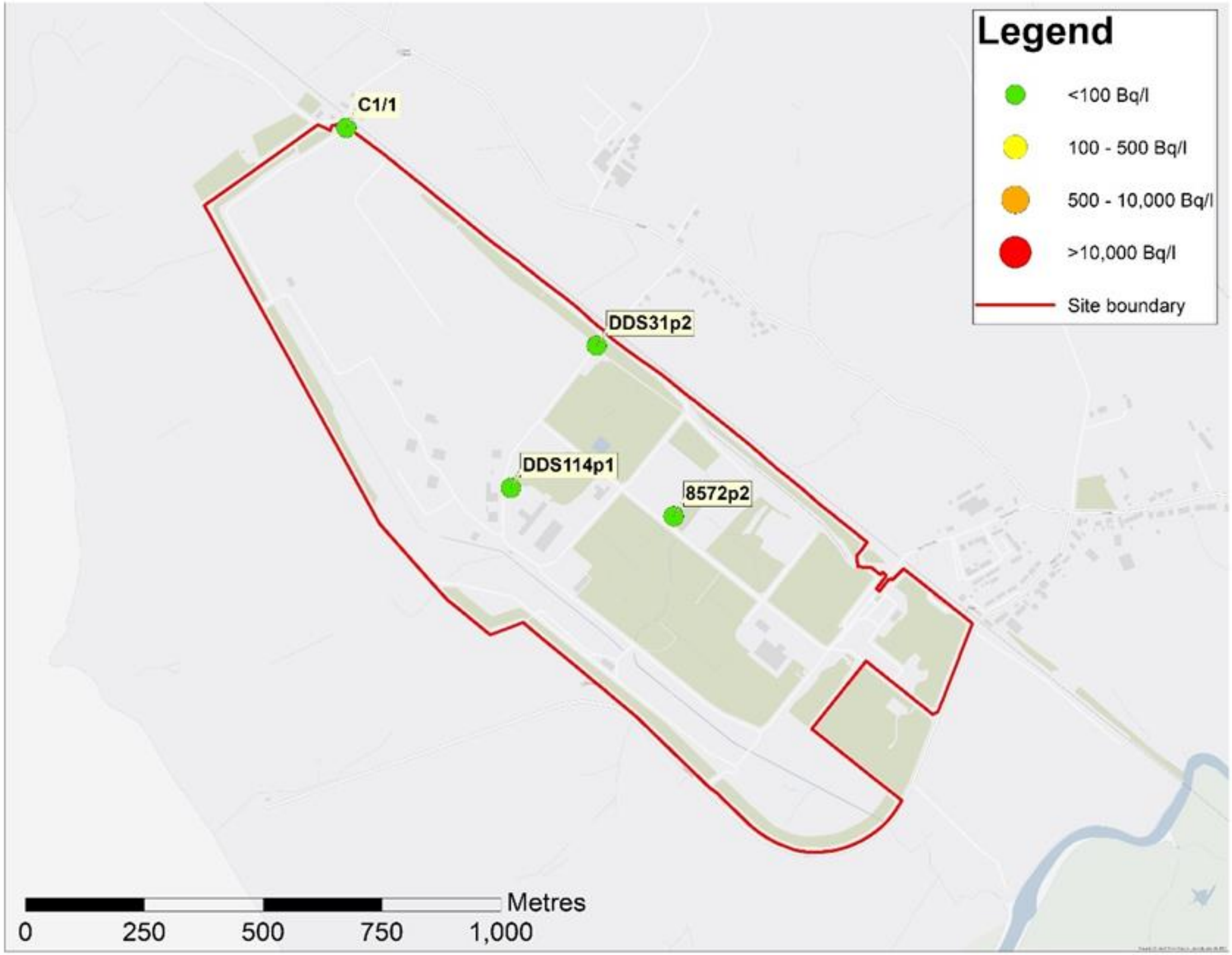


Figure 5.2: Tritium activity in Intermediate Groundwater 2024 to 2025 [37]

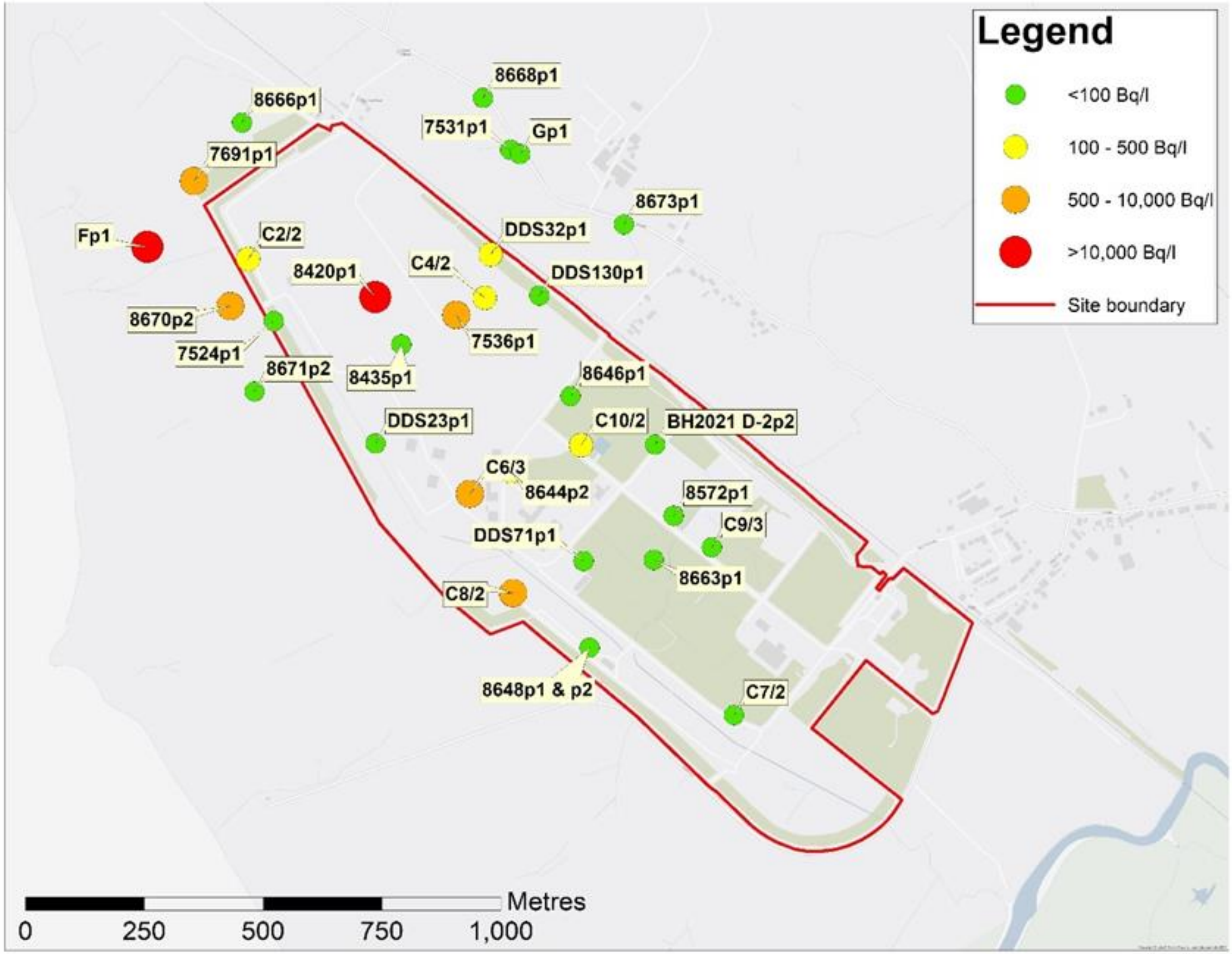


Figure 5.3: Tritium activity in Medium Groundwater 2024 to 2025 [37]

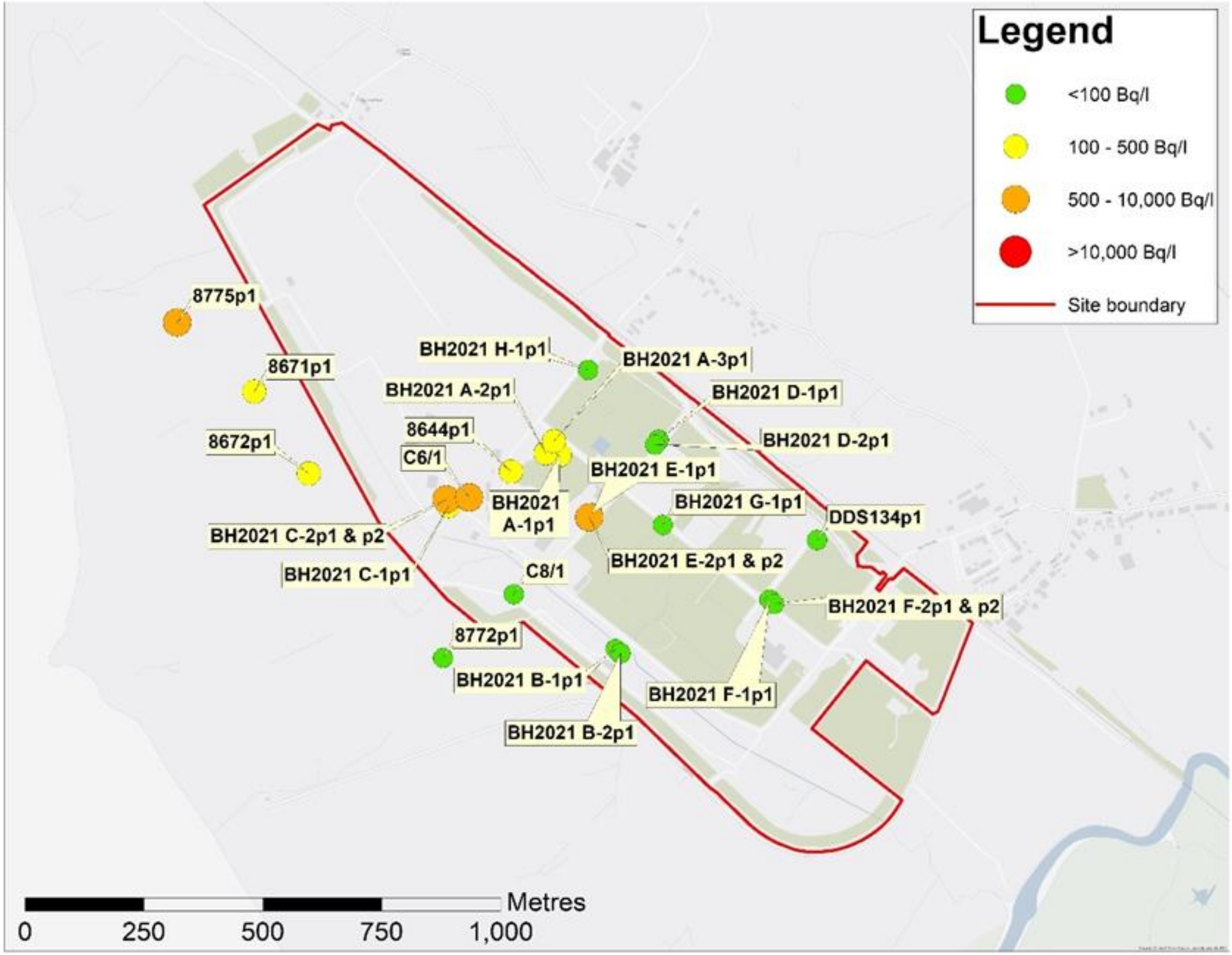


Figure 5.4: Tritium activity in Deep Groundwater 2024 to 2025 [37]

The groundwater monitoring data provide a way to assess how the repository has affected groundwater in the longer term. A general declining trend in tritium in the Upper and Intermediate Groundwater, is evident over the longer term with a slow decline in tritium in the Medium Regional Groundwater and an increase in tritium in the Deep Regional Groundwater, as shown in Figure 5.5 to Figure 5.8. This declining trend is attributed to radioactive decay, progressive leaching and the combined effect of capping of the trenches and cut-off wall installation. The interim cap has decreased infiltration into the waste and installation of the cut-off wall restricting lateral migration. The slight increase in tritium in Deep Groundwater since 2008 is due to the integration of site monitoring into a single programme, which allowed targeted monitoring in areas of concern and is not generally related to an increase in tritium activity concentrations. Figure 5.5 shows that the number of off-site Upper Groundwater monitoring points included for analysis was reduced in 2021 as a good baseline dataset had been collected and the majority were too shallow to show any impact from the site. Some have been retained for groundwater level monitoring and remain available for future analysis if required.

In more recent years, the levels remained similar although there is an overall downward trend. The increased tritium in Medium Groundwater, observed since 2013, is due principally to the elevated activities found in boreholes 8420p1 and Fp1. Tritium activity concentrations at both 8420p1 and Fp1 have reduced from their peaks in 2015 and 2016, respectively, as shown in Figure 5.9 and Figure 5.10. It is thought that the unusual peaks in tritium observed at these locations is due to the degradation of waste packaging or items in the trenches leading to a failure of the containment they offered and subsequent releases of tritium. This natural process may also have been accelerated by the loading of the cap by construction vehicles when carrying out cap and drainage repair works. It is expected that further peaks in tritium will be observed during and shortly after the capping operations we are due to undertake in the near term.

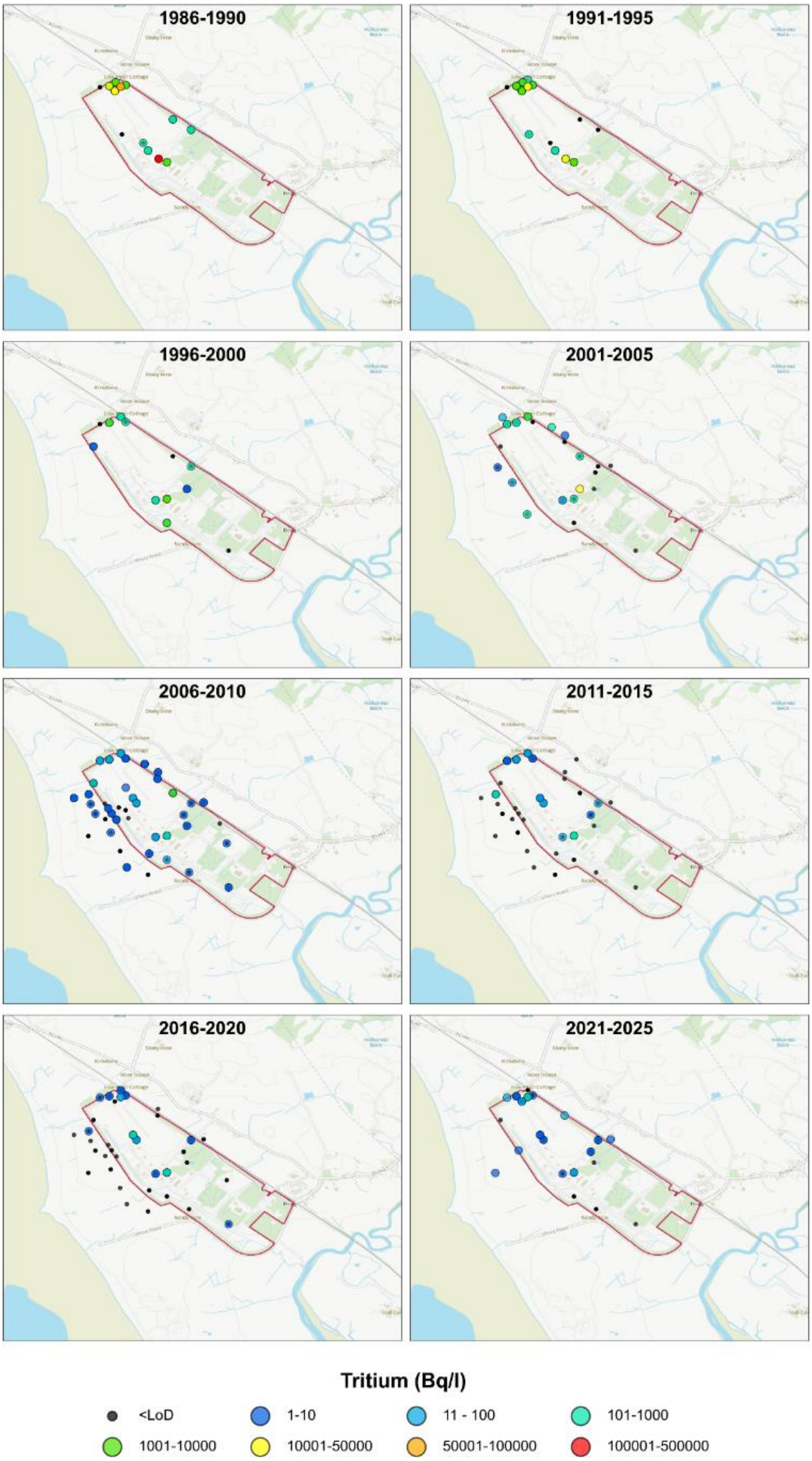


Figure 5.5: **Maximum tritium concentrations in Upper Groundwater 2008 to 2025**

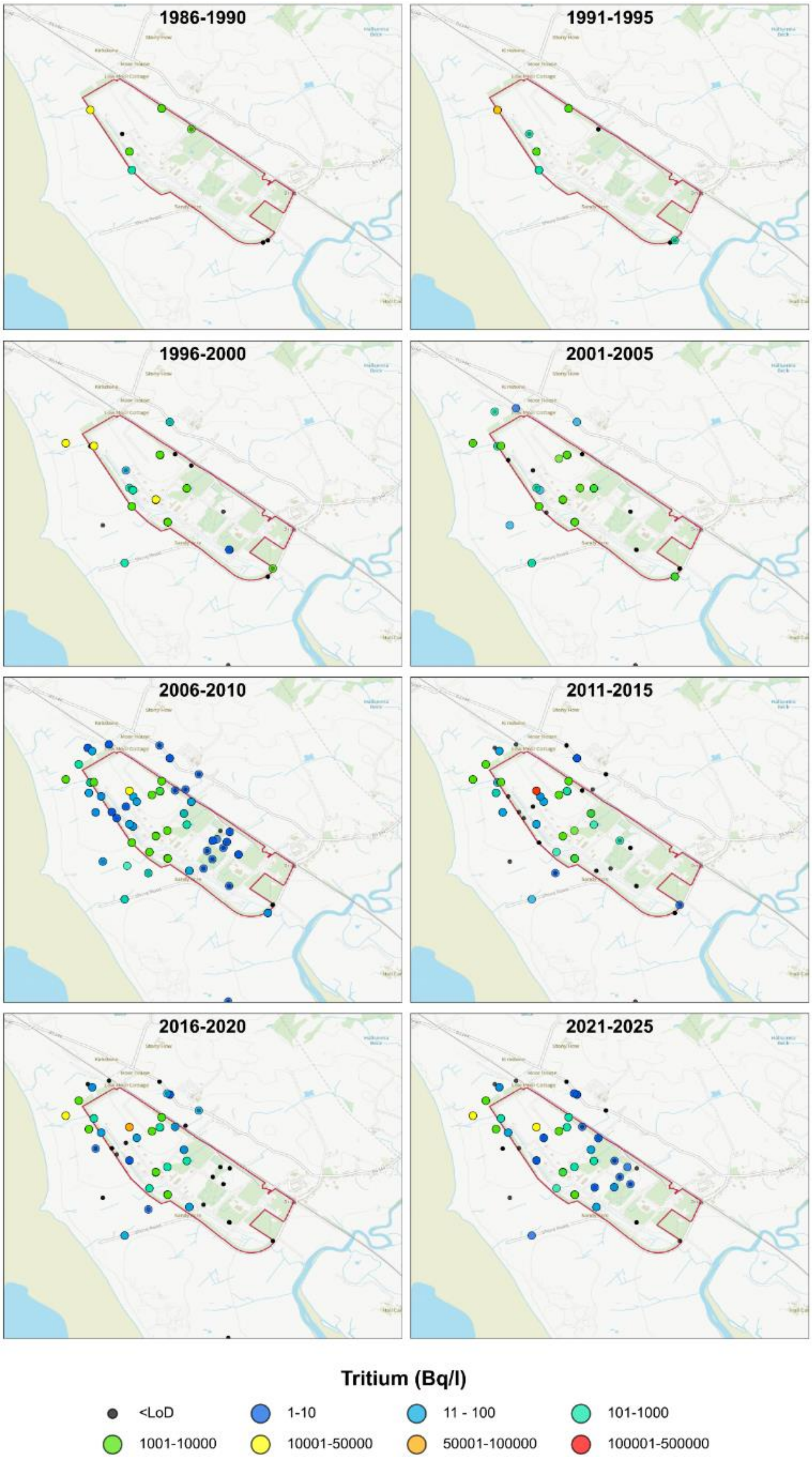


Figure 5.6: **Maximum tritium activity within the Medium Regional Groundwater 2008 to 2025**

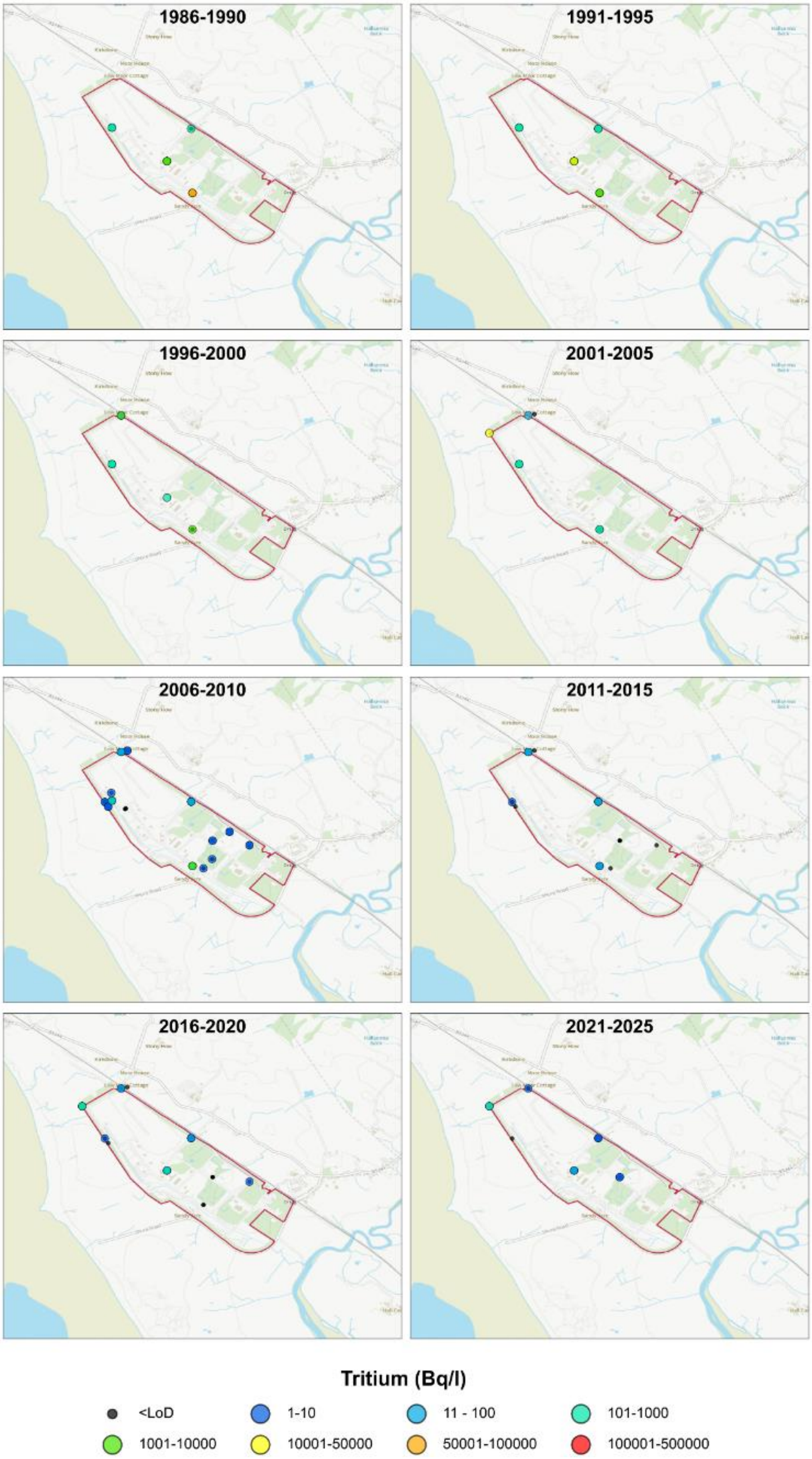
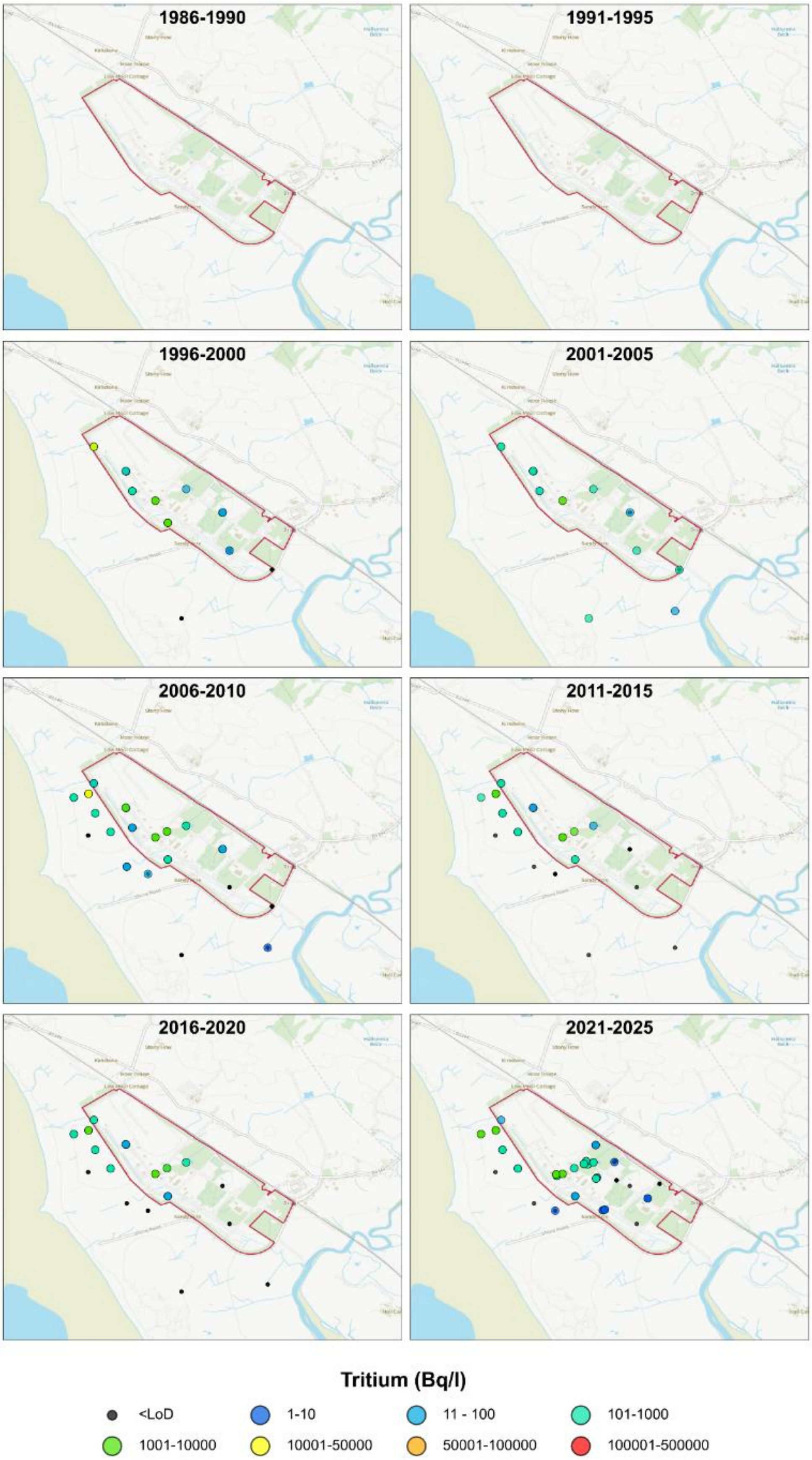


Figure 5.7: Maximum tritium activity within the Intermediate Regional Groundwater 2008 to 2025



1986-1990

1991-1995

1996-2000

2001-2005

2006-2010

2011-2015

2016-2020

2021-2025

Figure 5.8: 2024 Maximum tritium activity within the Deep Groundwater 2008 to 2025

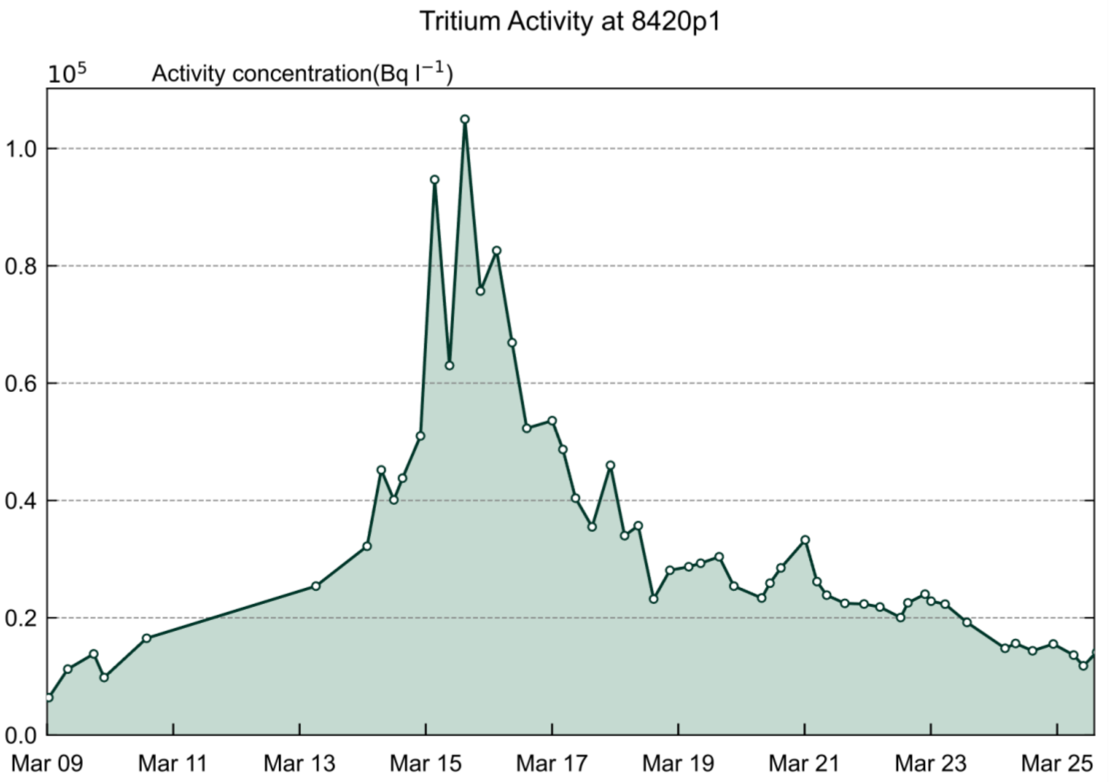


Figure 5.9: **Tritium activity at 8420p1**

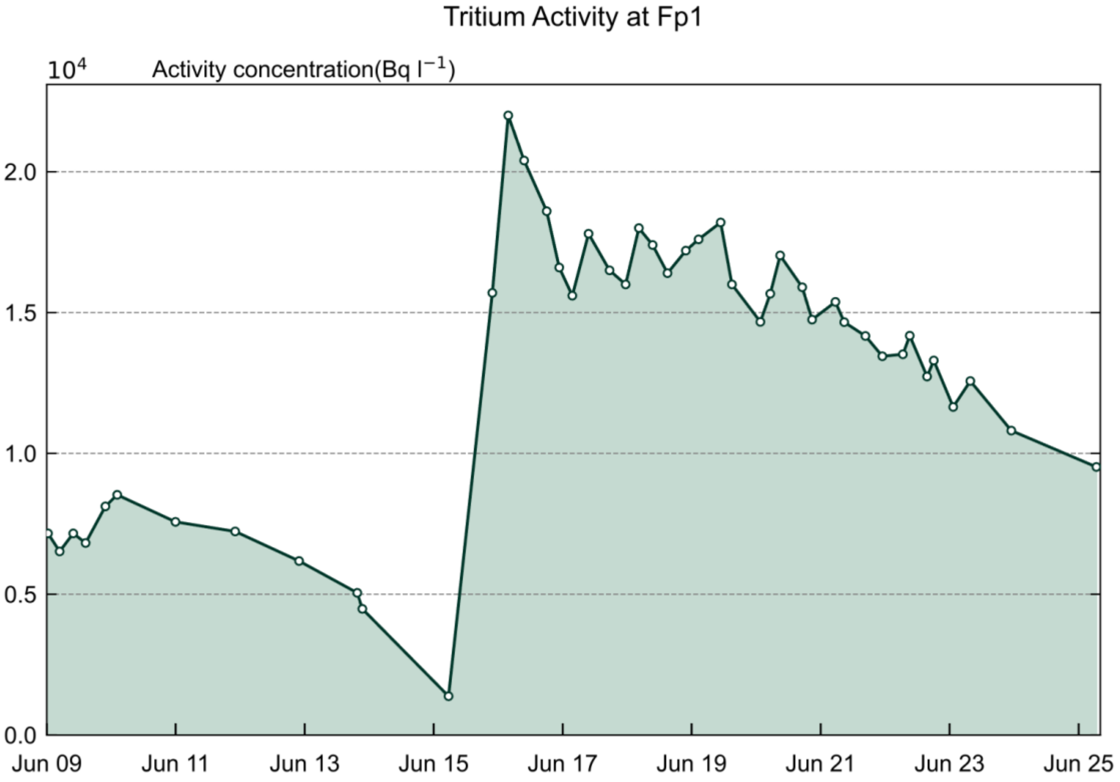


Figure 5.10: **Tritium activity at Fp1**

Total alpha and total beta in groundwater

Total alpha concentrations in 2024/25 across the site and in upstream and downstream locations continue to remain low within each of the groundwater systems and were only recorded above the limit of detection in a small number of monitoring locations. The concentrations were within the typical range for the locations, where recorded, and no rising trends have been identified that would indicate a change in the groundwater system. The highest total alpha concentration recorded on site was at DDS126p1. DDS126p1 is located immediately to the north of the trench disposal area. The highest concentration recorded upstream of the site was at Gp1, which is 200 m to the east of the site on the other side of the railway. Consistently elevated concentrations of total beta activity are also recorded at this location, which is considered to be too far up-gradient to be influenced by the disposal area on site.

In general, total beta activity levels in groundwater are also low at the majority of locations with only six greater than 1.0 Bq l^{-1}. The results recorded in 2024/25 do not indicate a change in the groundwater system in these locations. Four of the monitoring locations are on site and in close proximity to the trench disposal area. The other two are up-gradient of the site and are believed to be due to agricultural fertiliser use.

Gamma-emitting radionuclides in groundwater

Elevated concentrations of gamma-emitting radionuclides have not been observed in the groundwater.

Additional radionuclides

A link between carbon-14 and strontium-90 emerged in 2018 when it was discovered that the contracted laboratory's method for analysing carbon-14 could overestimate concentrations in the presence of strontium-90. This analytical interference led to the removal of several groundwater samples from the dataset until the issue was corrected. Elevated carbon-14 activity concentration was observed in groundwater samples taken from wells on and down-gradient of the LLWR site during 2019 [92]. Prior to 2020, the dataset for carbon-14 was too limited to allow a robust assessment of its spatial distribution or seasonal variation. This made it difficult to understand the full extent of carbon-14 releases from the LLWR site. As a result, a targeted monitoring investigation was launched during the 2020/21 monitoring year to fill these gaps.

During the 2024/25 monitoring year the 'watching brief' was maintained across 18 groundwater monitoring locations to confirm the locations where concentrations of carbon-14 and strontium-90 are present above their respective LLWRAS, and to identify any changes in the groundwater systems underlying the site. Carbon-14 analysis during 2024/25 has confirmed that activity concentrations above the LLWRAS (30.1 Bq l^{-1}) at three monitoring wells (8420p1, Fp1 and BH2021 C-2p2) as shown in Figure 5.11, with concentrations of 264 Bq/l, 61.7 Bq/l and 42.2 Bq/l respectively. Carbon-14 concentrations above the limit of detection are present in twelve other locations that are known to be hydraulically connected to the disposal area, however, they remain well below the LLWRAS (30.1 Bq/l).

Samples collected from 18 groundwater monitoring wells in 2024/25 confirmed the presence of strontium-90 above the LLWRAS (0.141 Bq/l) at seven locations all within the LLWR site and in close proximity to the disposal area (Figure 5.12). These strontium-90 results remain in the same range as those recorded in the previous year.

Alongside the carbon-14 and strontium-90 analyses at 18 groundwater monitoring wells, technetium-99 and chlorine-36 analyses were also carried out at five locations (locations where elevated tritium concentrations had previously been recorded) to further augment the available dataset. The highest levels of technetium-99 (0.107 Bql l^{-1}) were recorded in borehole 8420p1 adjacent to Trench 3 but remain below the LLWRAS (14.6 Bq l^{-1}). Detectable levels of chlorine-36 were also recorded at 8420p1 (1.1 Bq l^{-1}) with the highest level off site to the west at borehole Fp1 (2.31 Bq l^{-1}) also below the LLWRAS (8.1 Bq l^{-1}).

The source of technetium-99, chlorine-36, carbon-14 and strontium-90 is attributed to the trench disposals. Initially the exceedances were thought to be spatially linked and potentially from the same disposals but recent data do not support this correlation. As with tritium, the concentrations of these radionuclides are considered to be of low impact to the environment and pose no significant risk to members of the public. However, unlike tritium and strontium-90, carbon-14 has a longer half-life (5,730 years) and as such will persist longer as a potential source. For all these radionuclides, we expect that inputs to groundwater will be significantly reduced following completion of the capping operation works that we are currently undertaking.

Iodine-129 is not currently monitored routinely in groundwater or leachate as part of the ongoing environmental monitoring programme. However, historical leachate monitoring has been undertaken, most recently in 2015. Many results were below the laboratory limit of detection; where detectable, I-129 concentrations were typically around 0.1–0.2 Bq l^{-1}, with a maximum recorded concentration of 1.33 Bq l^{-1}. These measured concentrations are substantially lower than those calculated by assessment modelling [14], indicating that the assessment is conservative.

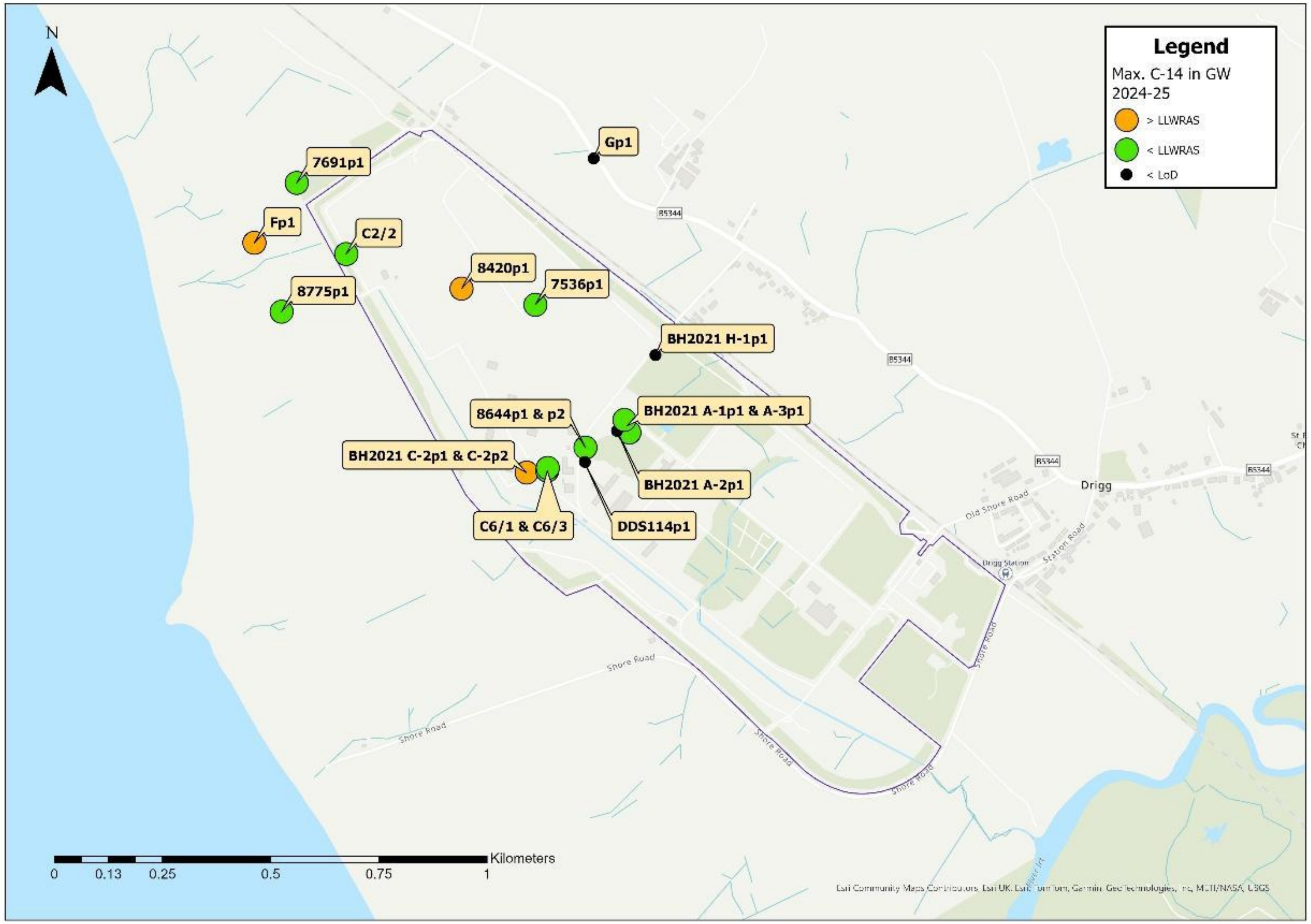


Figure 5.11: C-14 activity in Groundwater 2024 to 2025 [37]

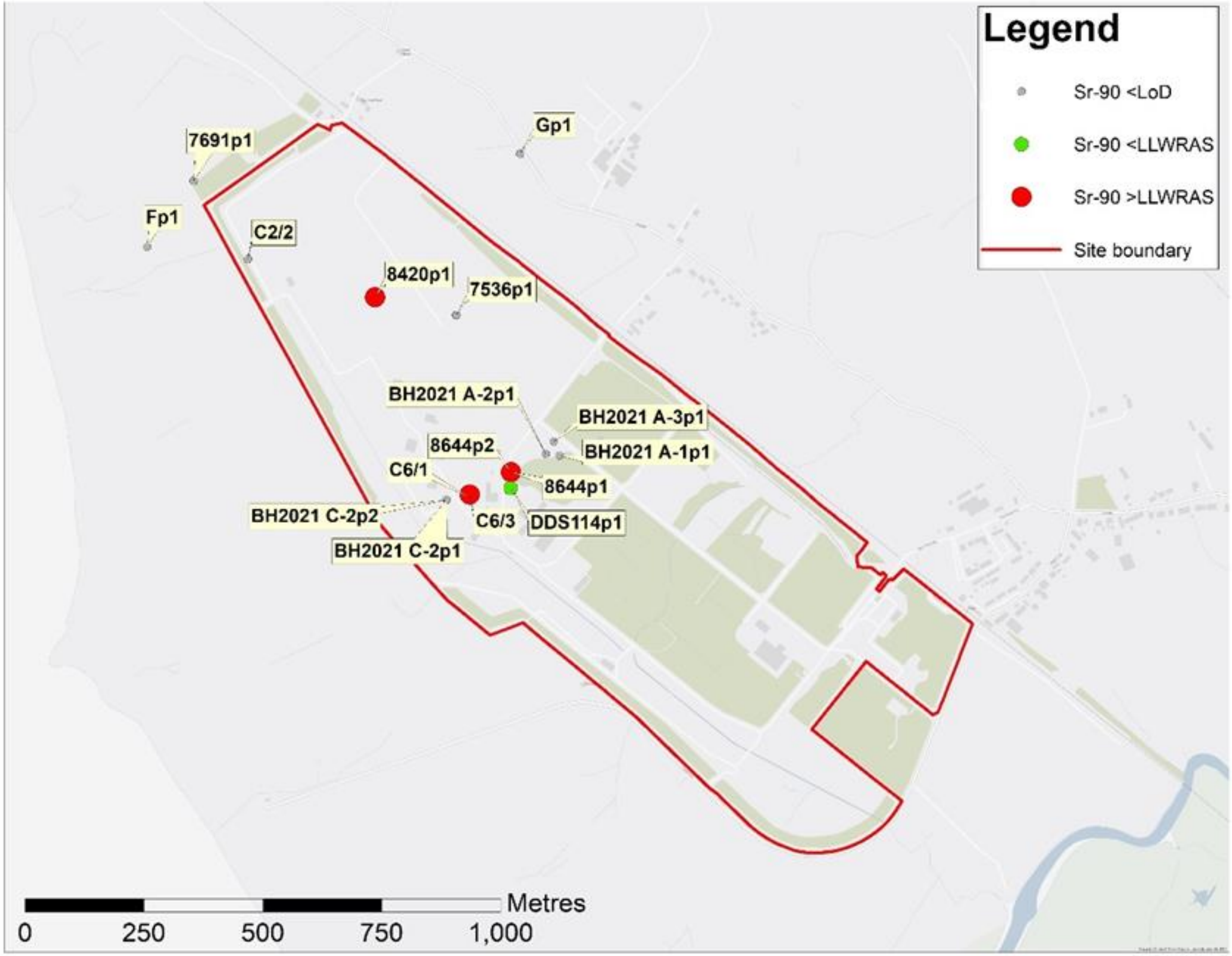


Figure 5.12: Strontium-90 activity in Groundwater 2024 to 25 [37]

5.3 Surface Water Radiological Monitoring Results

Tritium

Consistent with previous monitoring years, activity concentrations of tritium were detected at, or close to, the limit of detection (<5.00 Bq l^{-1}) at all locations, with the exception of the Lonesome Pine Weir and OF1 Weir. Concentrations of tritium are consistently recorded at Lonesome Pine Weir and OF1 Weir above the limit of detection but significantly lower than the LLWRAS (529 Bq l^{-1}). The elevated levels correspond to times of low flow and further investigations have been undertaken for both locations [41, 93, 94] which confirm this finding.

Lonesome Pine Weir is a surface water drainage discharge point into the Drigg Stream adjacent to the office complex on site. Quarterly monitoring during 2024/25 recorded a tritium activity concentration range of 10.6 to 23.6 Bq l^{-1}. These levels are similar to those observed in previous years. Low levels of tritium remain present in the shallow groundwater around the area to the south of the trench disposal area. The tritium continues to discharge into the surface water drainage system and hence is identified at the Lonesome Pine Weir during periods of low flow.

OF1 Weir is a land drain outfall to the Drigg Stream, south of the Lonesome Pine Weir. Monitoring results from OF1 Weir have consistently identified low activity concentrations of tritium (10 to 20 Bq l^{-1}).

A phased investigation was carried out to identify the tritium source. Dewatering works were carried out over a six-month period in the area to the north of the Fire Pond between July and September 2021 to enable the construction of Lagoon D as part of the enabling works for capping operations. Sampling in the pipework from these dewatering works and in the area downstream of the dewatering confirmed that these operations had caused the spike in activity at the OF1 Weir. A technical memorandum summarises the investigation undertaken and identification of the source [40].

Total alpha and total beta

Very low concentrations of total alpha activity were recorded in the river and surface water samples from 2024/25. The maximum total alpha activity that was detected in river water was marginally above the typical limit of detection (~0.02 Bq l^{-1}) but does not indicate influence from the LLWR site activities.

The majority of detectable results for total beta activity were recorded at low activity concentrations throughout 2024/25 and indicate that the impact to the surface and river water systems is largely indistinguishable from background measurements.

Gamma-emitting radionuclides

Very low levels of gamma-emitting radionuclides have been detected at river water and surface water locations in 2024/25. The activity is mostly associated with potassium-40 in river water samples from points along the East-West Stream and Drigg Stream but also surface water locations (GF0004 and SW12). Potassium-40 is a naturally occurring radionuclide, and these monitoring locations are thought to be locally influenced by agricultural run-off.

5.4 Performance of Engineered Barriers

It is important that engineered barriers perform in accordance with their original design intent. An assessment of these barriers is routinely undertaken to establish that they continue to operate and perform appropriately. Such assessments are carried out and reported annually in the '*Disposal Area Performance*' report [39].

5.4.1 Interim Cap Performance Assessment

In order to directly measure the performance of the interim trench cap, the quantity of water that percolates through the cap would have to be measured, which is not feasible. The performance of the interim trench cap has historically been inferred from the following observations:

- visual surveys;
- water balance modelling;
- interim trench leachate levels and temperature;
- groundwater quality data.

If water were percolating through the interim trench cap it would be expected that the following effects may be observed: higher leachate levels, leachate levels and temperature responding to rainfall events, lower run-off and/or higher leachate flows from the trenches.

Historically, cap efficiency has been used as a measure of the ability of the interim cap to prevent rainwater from infiltrating into the waste. The effectiveness of the interim trench cap can be estimated by comparing the run-off from the cap into the perimeter drains with the Hydrological Effective Rainfall (HER) calculation. If the cap is 100% efficient, then all HER will become run-off. Trench cap efficiency is estimated by water balance modelling. It is accepted that the calculation is only an estimate with inherent uncertainties and approximations that mean that the resulting efficiency figure can only be used as a general indication of cap performance. Efficiency values greater than 100% can arise due to uncertainties in water balance modelling, especially when:

- run-off measurements are overestimated due to temporary drainage enhancements;
- HER is underestimated, particularly during dry spells or when rainfall data are interpolated;
- probe hole drainage or surface water diversion temporarily increases measured run-off beyond expected HER

It is known that the current interim trench cap is suboptimal in performance and therefore a programme of work to replace the interim cap commenced in 2025. The suboptimal performance was primarily identified from the cap efficiency calculations, which indicated significant variation between years, as illustrated by Figure 5.13. This was initially attributed to potential inflow around probe holes [95] but intrusive investigations demonstrated that the interim membrane had been damaged during the construction of the interim cap [96]. As a result, the interim trench cap model was calibrated to incorporate potential gaps along approximately 30% of the seams where the geomembrane strips should otherwise be jointed [97].

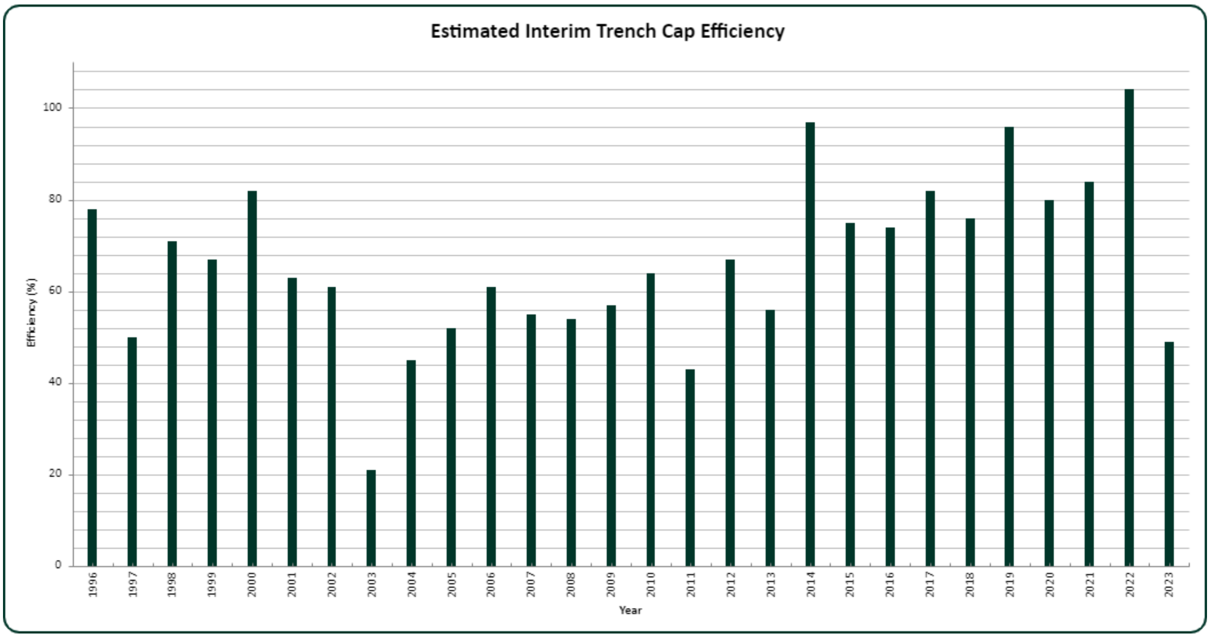


Figure 5.13: Estimated interim trench cap efficiency [39]

Work to replace the interim trench cap membrane included the decommissioning of the trench cap weather station, installation of new herringbone drainage to aid drainage of the cap membrane overburden, and the optimisation of the probe hole drainage network; all of which introduced more uncertainty into the water balance calculation. Further works through 2025/26 are expected to involve the stripping of surficial cover, penetration of the aging cap membrane, and installation of significant quantities of new fill and a sealed membrane. With such additional uncertainties, the value of modelling cap performance during this construction phase using existing parameters is limited and potentially misleading, and so the water balance model has not been undertaken in the 2024 performance assessment. Multiple lines of evidence are used to measure performance, including visual (UAV) surveys, cap performance modelling, leachate levels and temperatures and groundwater quality. The visual surveys, trench leachate levels and temperature and groundwater quality data can also provide confidence that significant rainfall volumes are not entering the trenches through the interim trench cap in the absence of water balance data.

Measuring leachate level and temperature in the trenches provides information regarding the infiltration of water through the interim trench cap by allowing comparison of the effect of rainfall events on leachate level and temperature within the trenches.

The data collected are analysed to ascertain cap performance and other changes within the system including the visualisation of:

- rainfall data plotted against leachate level at probe holes;
- rainfall data plotted against leachate temperature at probe holes;
- leachate levels along each trench in comparison with membrane level;
- leachate levels along each trench in comparison with historically measured levels.

Leachate levels are also compared with historically measured maxima and minima at each probe hole in order to assess whether data remain within the bounds of that collected previously.

The leachate level responses occur gradually throughout the year, indicating that the level changes are not localised to the individual probe hole and indicative of a potential fault in the interim cap at that location. The levels observed in P4.1 are shown in Figure 5.14.

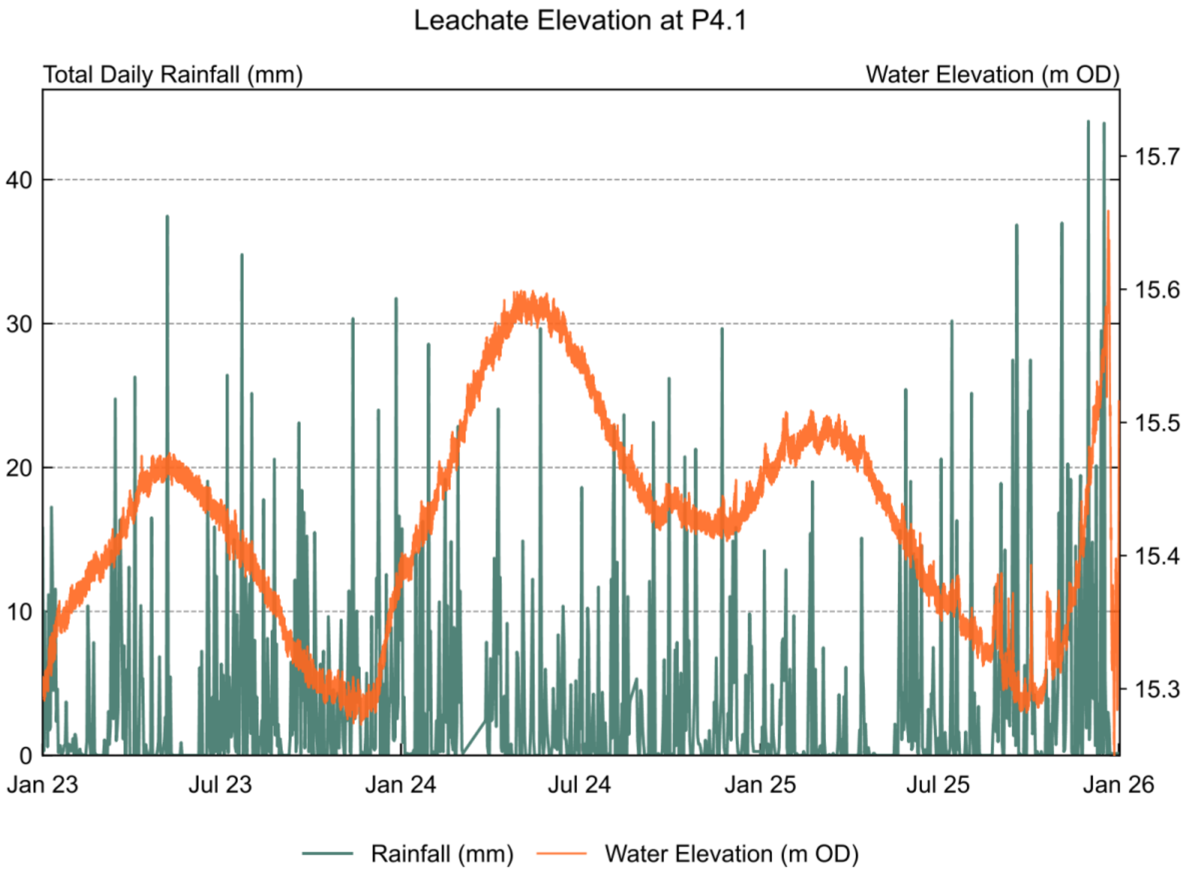


Figure 5.14: Leachate Elevation at P4.1

Some probe holes have shown more erratic behaviour in the past which may indicate a response to rainfall due to a local fault in the interim cap. Leachate levels at P3.8 show a range of approximately 2 m since 2023 as shown in Figure 5.15.

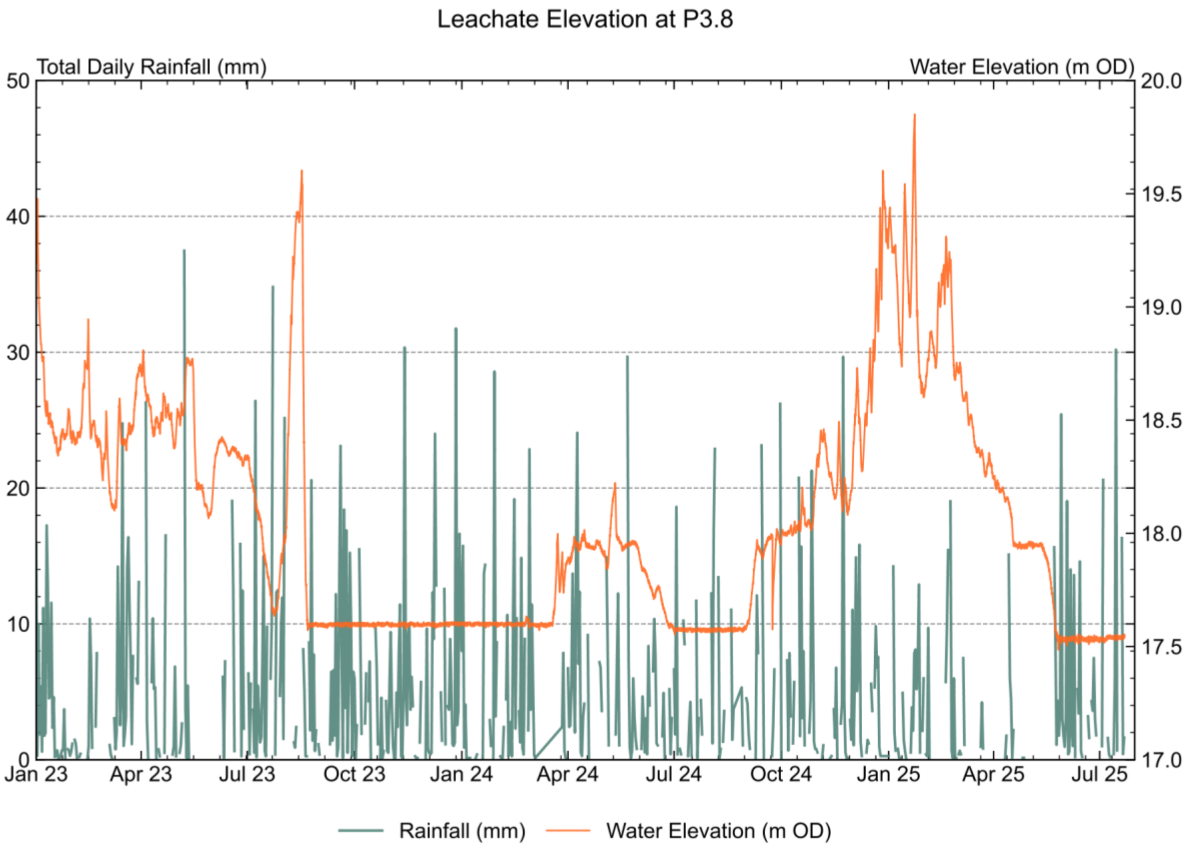


Figure 5.15: Leachate elevation at P3.8

In general, probe holes show a reduced leachate level compared with their historical average levels, as illustrated by Figure 5.16, indicating a general reduction in leachate levels over time due to the placement of the interim cap.

As noted in Subsection 5.2, tritium levels in the Upper and Intermediate Groundwater have declined over the longer term with a slow decline in tritium in the Medium Regional Groundwater and an increase in tritium in the Deep Regional Groundwater, as shown in Figure 5.5 to Figure 5.8. The decrease can in part be attributed to the reduction of water infiltrating into the waste due to capping.

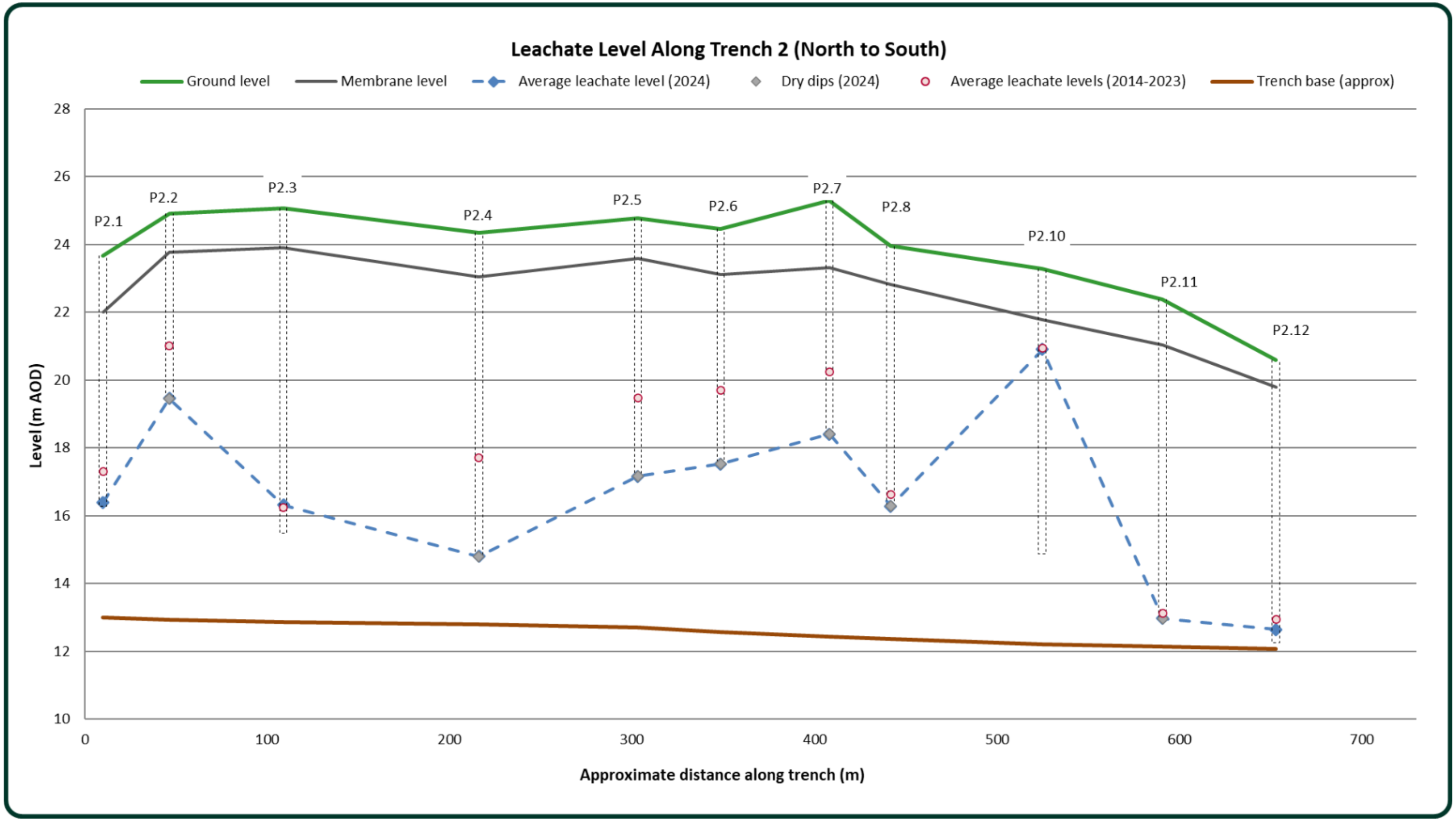


Figure 5.16: Leachate level along Trench 2 [39]

5.4.1.1 Assessment of the Performance of the Cement-bentonite Cut-off Wall

The cut-off wall to the north and east of the trenches was constructed to provide a barrier against the:

- egress of leachate from the trenches to the north and east;
- ingress of groundwater from the surrounding geology.

As shown in Figure 5.17, the cut-off wall originally only bordered the north and east of Trenches 1 to 6. It is approximately 1 m wide, 450 m long and 9 m deep. An approximately 350 m extension, with similar installation details, was installed along the eastern side of Trench 7 in 1995.

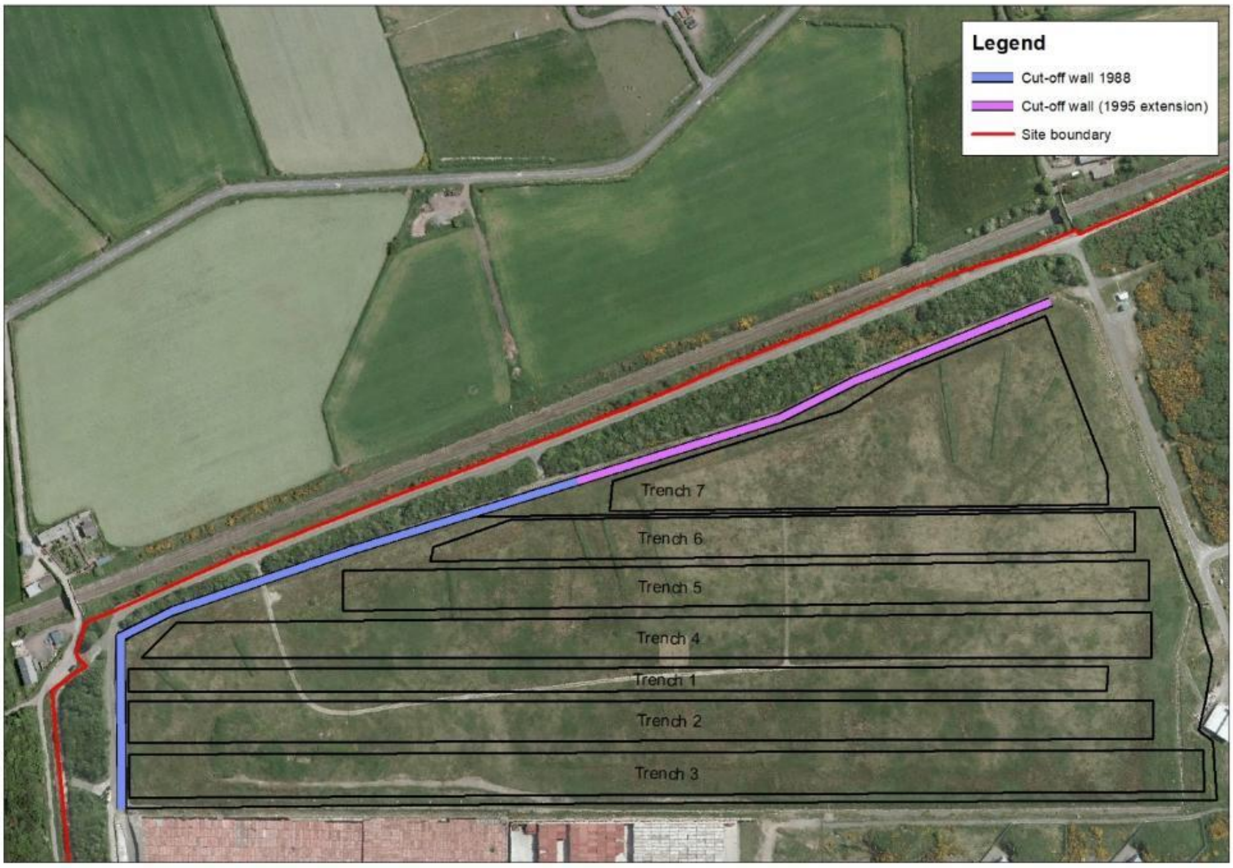


Figure 5.17: Trench cap cut-off wall location

The performance of the cut-off wall is assessed using observations of groundwater quality and levels in boreholes close to the cut-off wall and observations of surface water quality at GF0004.

Groundwater quality adjacent to the cut-off wall

The low tritium activity concentrations present within the Upper Groundwater divisions indicate that there is limited horizontal migration of tritium from the trenches and confirm the predominantly vertical movement of previously released tritium to the Regional Groundwater. Upper Groundwater data immediately to the east of the trenches indicate tritium migration continues to be restricted by the cut-off wall and that there is no sign of degradation in this structure.

Water level across the cut-off wall

Comparison of water levels in the Upper Groundwater north-east of the cut-off wall (outside) and in probe holes immediately south-west of the cut-off wall (inside) gives an indication of the degree of connectivity of the water systems across the boundary. This acts as a cut-off wall performance indicator.

Groundwater wells monitoring the Upper Groundwater system were identified outside and adjacent to the cut-off wall. The levels observed in each groundwater well during 2024 were compared with levels observed during the same period at the closest trench leachate probe hole to each well. The results of the comparison can be found in Table 5.1.

Table 5.1: Comparison of average water levels across the cut-off wall

Locations	Upper Groundwater level (m AOD)	Trench leachate level (m AOD)	Difference (m)
7521p1 and P7.1 Adjacent to northern end of Trench 7	17.29	15.32	1.97
C1/2 and P4.1 Adjacent to northern end of Trench 4	16.96	15.51	1.45
DDS126p1 and P3.1 Adjacent to northern end of trench 3	17.81	16.98	0.83

Comparison of the data collected during 2024 illustrates that Upper Groundwater levels remain higher than those observed in trench leachates and that connectivity between the two systems is limited. Figure 5.18 displays the difference in levels across the cut-off wall since 2015 and shows a generally stable difference that indicates cut-off wall performance is not deteriorating although it is noted that the there is an apparent trend in decreasing difference between 7521p1 and P7.1 adjacent to the norther end of the Trench 7.

Surface water quality in the railway drain

Elevated tritium levels were historically found at a railway drain (GF0004) directly to the east of the LLWR site. The low tritium activity now at GF0004 (Figure 5.19) and the absence of elevated tritium concentrations in boreholes screened above the cut-off wall, on the eastern boundary of the site, indicates that the cut-off wall is successfully acting as a barrier to contaminant migration in the Upper Groundwater on the eastern boundary of the trenches. The groundwater levels outside the cut-off wall also indicate that migration would be towards the west rather than towards the railway cutting.

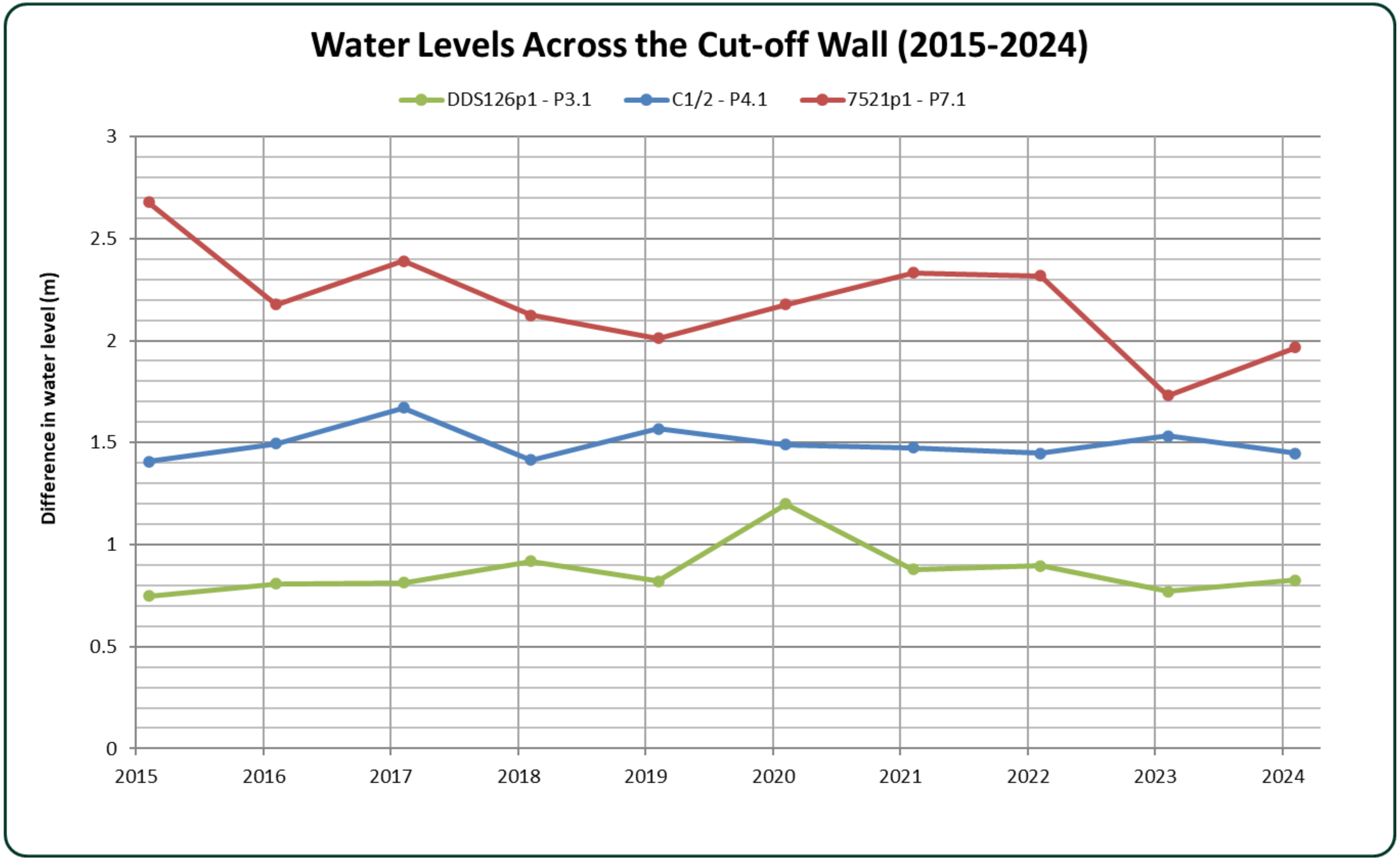


Figure 5.18 **Water levels across the cut-off wall (2015 to 2024) [39]**

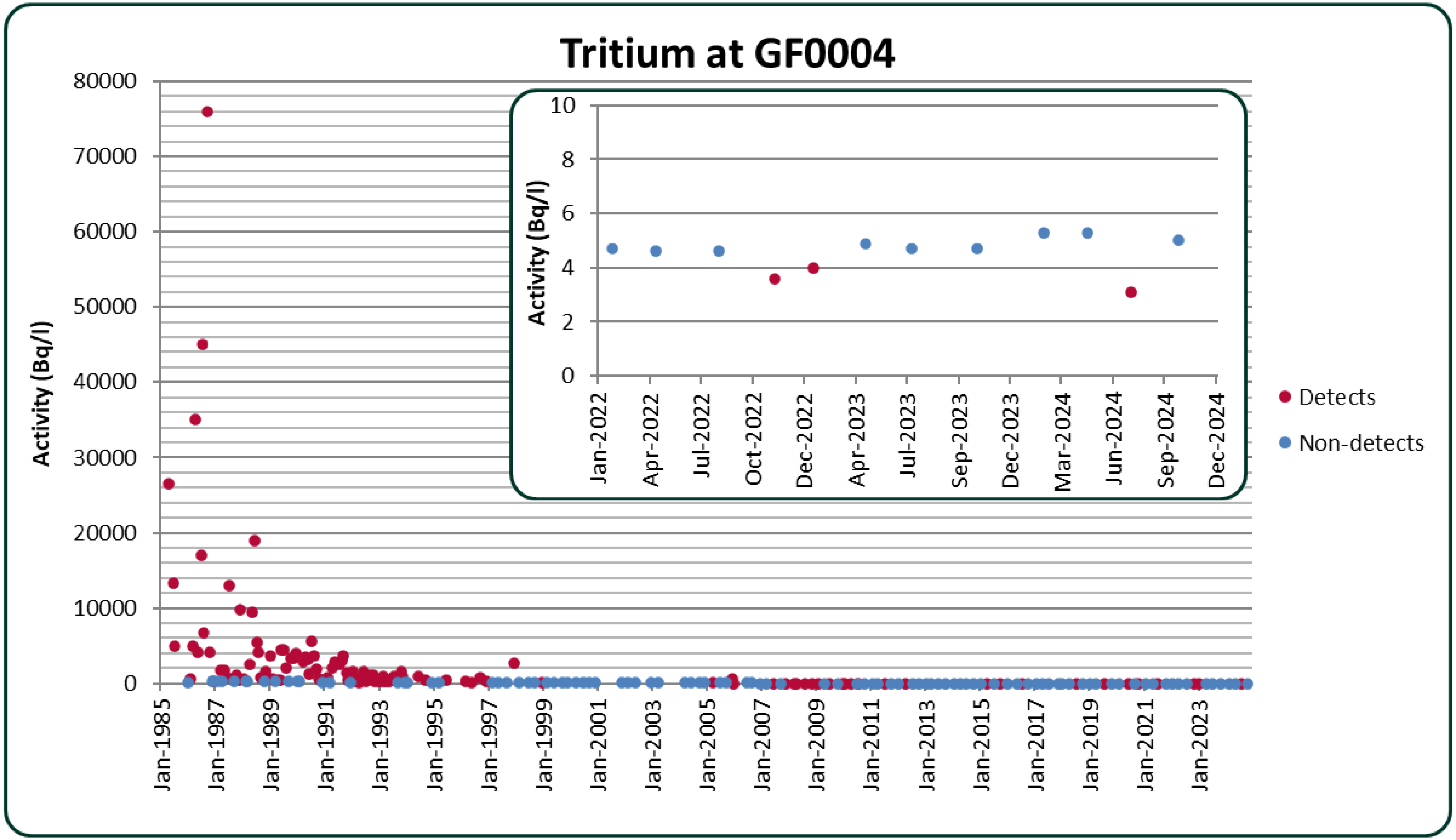


Figure 5.19: Tritium at the GF0004 monitoring point [39]

5.4.2 Leachate and Authorised Discharges

5.4.2.1 MHT Discharges

Leachate from the trenches and vaults is collected in the MHT and then discharged via the Marine Pipeline. A proportional sample of MHT leachate is collected from each discharge and bulked into weekly samples for radiological analysis. The weekly samples are subsequently bulked on a monthly basis for additional analyses. The results of these are used to calculate the activity of aqueous discharges to the Irish Sea. Monthly spot samples are collected to ensure conformance with the Permit requirements.

The radioactivity in the discharged leachate has remained consistent with that in previous monitoring periods, as shown in Figure 5.20. The environmental risk assessment for aqueous discharge from the LLWR provides evidence that both radiological and non-radiological discharges through the pipeline continue to have a negligible impact on the environment [79].

5.4.2.2 Gaseous Effluent Discharges

The Permit requires gaseous effluent discharge monitoring from active discharge stacks. Site stack discharges are continuously monitored with sample filter cards, which are bulked for radiological analysis on a quarterly basis. The monitoring results are used each quarter to calculate the total activity discharged to the environment. Total alpha and total beta annual aerial total discharges declined significantly in 2019, as shown in Figure 5.21.

At the start of 2019, the site had six operating stacks, each with dual HEPA filtration systems installed. During 2019, four of the six stacks were removed as part of magazine decommissioning. Decommissioning included removal of all extraction and filtration systems, including the installed stacks.

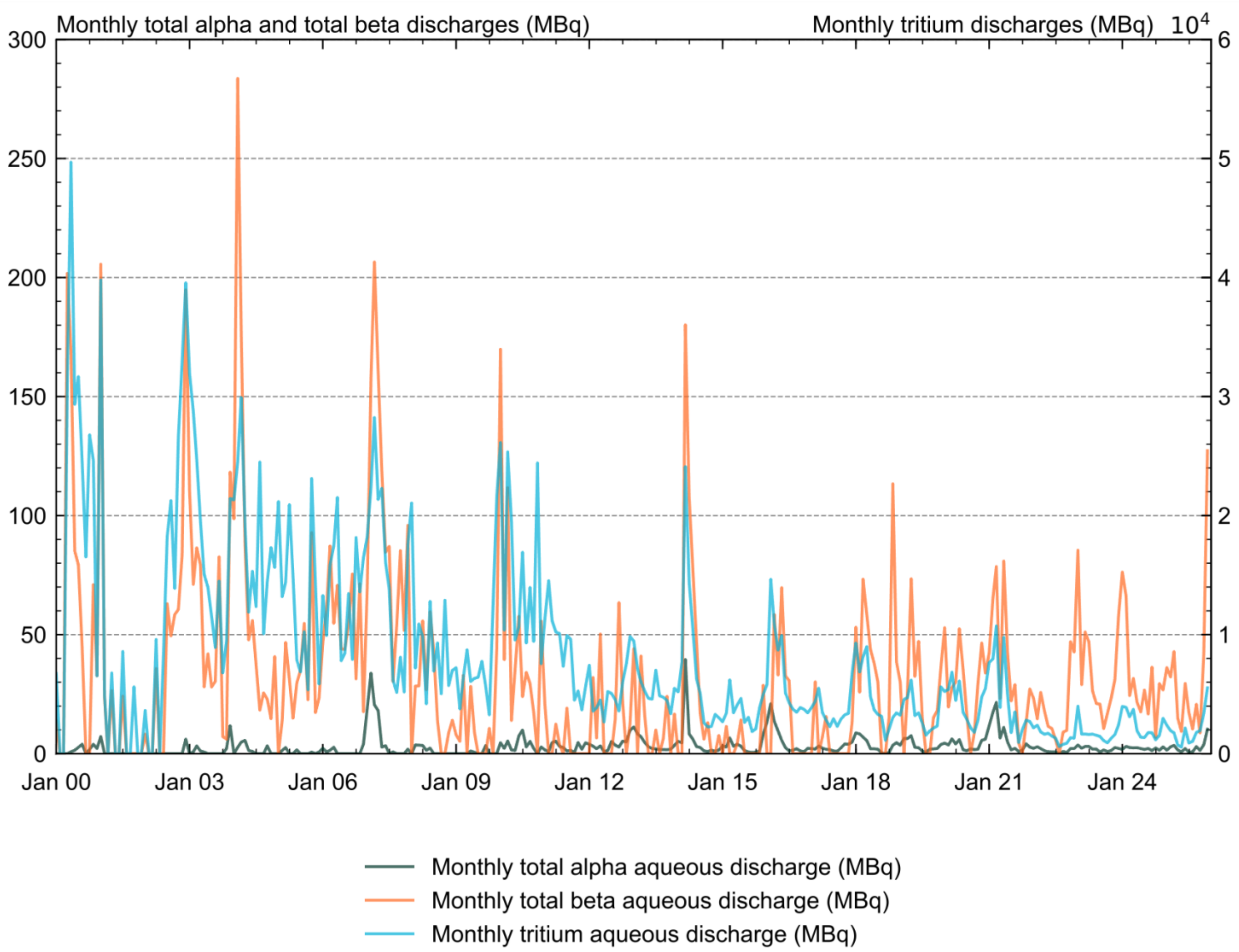


Figure 5.20: Monthly MHT discharges 2000 to 2025

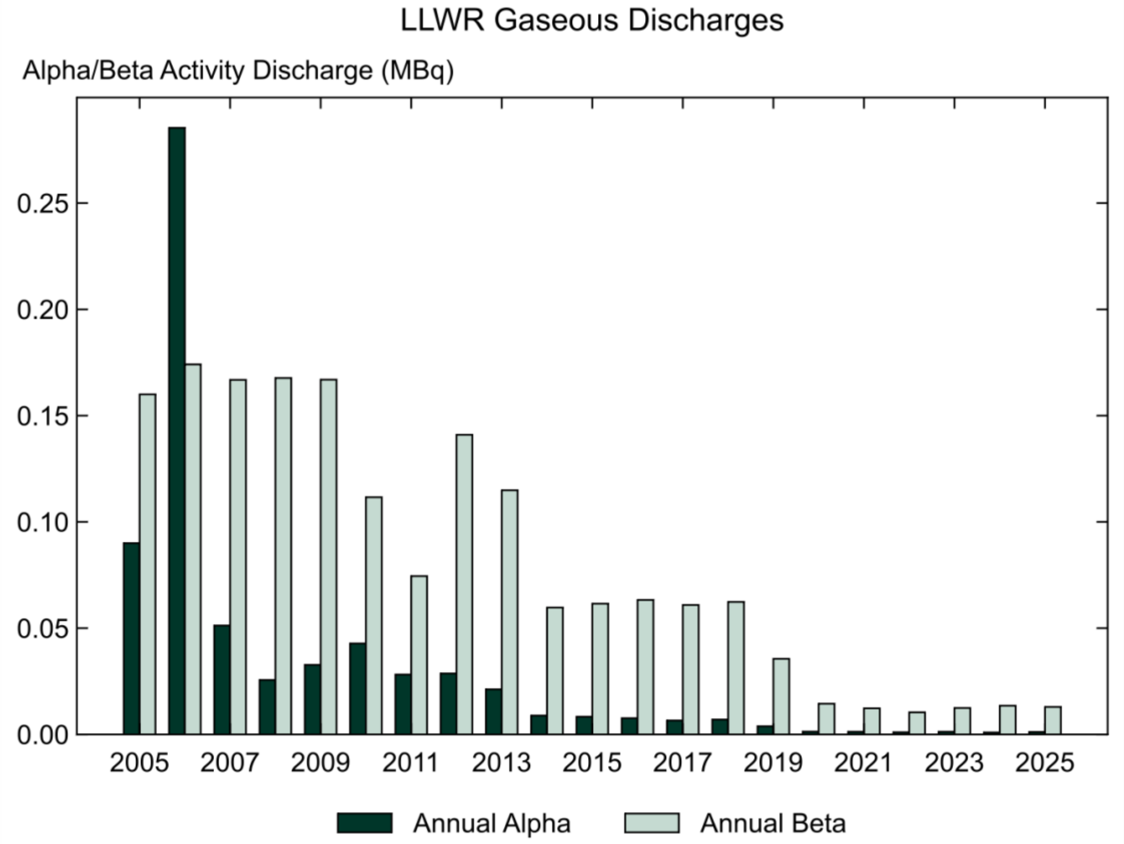


Figure 5.21: Gaseous effluent discharges from the LLWR site (2005 to 2025)

5.4.2.3 Dose Rate Monitoring

The annual external radiation dose calculation uses dose rate data collected from the thermoluminescent dosimeters deployed around the site perimeter fence and is calculated for three different groups of members of the public to assess the potential direct radiation dose for the most exposed group. The three groups are:

- itinerant members of the public adjacent to the site perimeter fence, such as dog walkers;
- coal yard employees working alongside the north-western side of the site perimeter opposite Vault 8;
- local residents living adjacent to the site perimeter.

As in previous years, local residents living adjacent to the site perimeter are the members of the public who are expected to receive the highest dose. The maximum individual direct radiation dose is estimated to be 25 µSv for 2024 after subtraction of background. The dose estimate was made using a conservative assumption of 100% residential occupancy, of which 90% was indoors. A shielding factor of 0.2 is applied to indoor occupancy (for standard family house construction of brick/stone). The assessment also conservatively assumes that occupancy is at the perimeter fence rather than at the actual dwelling. It is noted that this is conservative in comparison to the approach used in the PoA assessment [13].

The calculated retrospective dose is dominated by the external irradiation dose. The background radiation level is large in comparison with the representative person direct radiation dose, as is the measured variation in background levels. The measurement uncertainty is therefore relatively high.

The calculated 2024 annual dose of 25 µSv remains low in comparison with the 300 µSv requirement in the GRA and very low in comparison with the 1,000 µSv legal dose limit to other persons (i.e. members of the public) under Ionising Radiation Regulations [99]. It is considered to be insignificant in comparison to the 2,200 µSv annual average UK dose rate due to natural background radiation.

5.4.3 Gas Generation and Migration

5.4.3.1 Landfill Gas Volume and Quality

During the 2024/25 reporting period, four of the eleven sealed probe holes recorded methane levels above the lower explosive limit (5% by volume of air), with one of these locations (P7.3) consistently above this lower explosive limit. In each instance the flow rate of gas at these locations was very low, therefore, any methane present would be quickly dispersed upon leaving the probe holes. As a result, the risk of ignition at locations where methane is present is considered negligible. Elevated concentrations of methane were also recorded in several unsealed probe holes. The recorded concentrations fluctuated across the monitoring period and do not appear to indicate a change in landfill gas generation in these areas. Landfill gas production from the trench disposal area is low when compared with a municipal landfill facility.

As gas flow rates recorded at the sealed probe holes are consistently very low, we consider there is negligible chance of a fire in the probe holes. The presence of methane might be associated with a potential fire within the trench waste material, if ignited. However, the proportion of combustible waste within the trench disposals is low, much of the waste is saturated and oxygen concentrations are low. It is, therefore, considered unlikely that a sub-surface fire could be maintained in the trench disposal area [100].

5.4.3.2 Landfill Gas Migration

Landfill gas migration was monitored at eighteen locations (perimeter wells) around the perimeter of the LLWR and in fourteen on-site buildings in 2024/25. Gas pressures in the perimeter wells were generally very close to atmospheric pressures; typically, no gas flow was observed. However, in March 2018, a positive flow of gas, with a peak flow of 3.60 $l\ h^{-1}$, was recorded at 7516p1. Further monitoring was undertaken three days later, and a negative flow rate was recorded. An investigation into the cause of the high flow variability at this location concluded that all gas composition measurements from this location were atmospheric and changes in flow rate are linked to peaks and troughs of pressure at the monitoring well relative to the atmosphere [101]. This effect remained evident at 7516p1 throughout the 2024/25 monitoring year and ranged from a negative flow of $-64.2\ l\ h^{-1}$ to $+0.5\ l\ h^{-1}$. The effect is referred to as barometric pumping and may indicate that the borehole intersects an area of high permeability with an overlying low permeability layer allowing pressure differences develop between the subsurface and the atmosphere [102].

One perimeter borehole showed elevated methane levels during 2024/25. However, the borehole is located >450 m from waste disposals and no locations between this location and the disposal area show similar elevated levels. Waste disposals have therefore been discounted as a viable source of methane to this location. The elevated methane recorded is thought to be due to a peat stockpile placed adjacent to the borehole. The gas composition at the remaining sixteen perimeter wells were within normal atmospheric concentration limits throughout the monitoring year and, thus, did not display any evidence of landfill gas migration.

5.4.3.3 Probe Hole Radioactive Gas Monitoring

The concentration of carbon-14 present in gas released from the monitoring locations continue to remain low. As gas flows at the monitored locations are generally negligible, significant amounts of gaseous carbon-14 are not being discharged from the trench disposal area. In conjunction with the analyses of carbon-14-bearing gases, the same seven sealed probe hole locations were used to obtain an in-situ radon and thoron measurement using passive alpha track detectors over a period of three days. A wide range of concentrations have been recorded year on year, which may be influenced by changes in atmospheric pressure during the monitoring period, when a drop in atmospheric pressure can cause barometric pumping of gases. The 2024/25 radon and thoron results in gases collected from probe holes have generally recorded decreased concentrations compared with those from 2023/24. This suggests there has been little change in the evolution of the waste at these locations within the trench disposal area.

5.4.3.4 Radon Monitoring

Radon activity concentrations were measured at a quarterly frequency from four locations along the spine of the disposal trenches and six locations around the perimeter of the disposal area. During the 2024/25 monitoring year, all the measured radon concentrations in the disposal area were below the DQF threshold level ($100\ Bq\ m^{-3}$).

Radon activity concentrations in Vault 8 and Vault 9 are monitored on a quarterly basis. Alongside this monitoring, passive radon detectors were deployed in three fork-lift trucks that are used in operational areas where radon exposure is possible at Vault 9, the DGF and the rail sidings. All measured radon concentrations were below the DQF threshold level ($100\ Bq\ m^{-3}$).

Twenty-six passive radon detectors were deployed in 13 buildings between November 2024 and February 2025. The detectors were deployed during the winter period because the closure of windows and doors reduces ventilation of the buildings. This allows worst-case radon activity concentrations to be measured. As with the data reported in previous years, all of the locations had radon activity concentrations below the DQF ($100\ Bq\ m^{-3}$) and the

Ionising Radiation Regulations (2017) [99] threshold level (300 Bq m^{-3}). The exception to this was at B704.9, which is located on the leachate drainage line and has regularly exceeded the 100 Bq m^{-3} DQF limit. During 2024/25 the radon result at B704.9 was 678 Bq m^{-3}. This result is above the DQF upper value of 100 Bq m^{-3} and the regulatory threshold level of 300 Bq m^{-3}. B704.9 is above the confluence of the leachate lines from the vaults and trenches, therefore, an elevated concentrations of radon is expected. B704.9 is not occupied on a frequent basis and thus exposure to the workforce is minimal. B704.9 recorded a radon concentration of 5,200 Bq m^{-3} in 2011. At this point, action was taken and ventilation was added to the building as well as the requirement to open the door and wait for 30 minutes before entering. B704.9 will continue to be monitored on an annual basis. Discussion is underway to assess if further restrictions are required before entering B704.9.

6 Use of Monitoring Data in Developing the Environmental Safety Case

The discussion in this subsection is focused on identifying the various uses of environmental monitoring data in the assessment to demonstrate that data are being appropriately used and that our conceptual and numerical models are well founded. It outlines how the monitoring data and modelling approaches have been used in a complementary way to build confidence in site and system understanding. Technical detail is not provided here, but references are cited for more detailed information on the use of data and the basis for conceptual and numerical models. Overall, the measurements in different media support the conclusion that the repository is having a limited impact on the surrounding environment. All the data are made available via the MonitorPro database, annual reports and via the GIS system which allows the monitoring locations to be visualised and incorporated into the site hazard maps. The results are also discussed at the bi-annual meetings between the ESC and Monitoring Teams. The environmental programme has developed over many years and, as the majority of the data is only available from late 1980s, that data are not available to establish baseline conditions prior to the start of disposals or prior to the start of the use of the site as an ordinance factory. Up-gradient monitoring is used to establish background conditions.

6.1 Development of the Hydrogeological Model

As noted in Subsection 2.2 the geological conceptual model has been updated following recent site investigations [23]. This has been used to develop the hydrogeological conceptual model [24] and the hydrogeological model [103], to support the safety assessments for the 2026 ESC. Both draw on a range of data provided by the environmental monitoring programme, including groundwater levels, water quality data, stream data and meteorological records. In particular, the hydrogeological model has been calibrated against observed groundwater heads. A hydrogeological model has been developed and calibrated and is reported in reference [103]. This model draws on a range of data provided by the environmental monitoring programme, including groundwater levels, water quality data, stream data and meteorological records. In particular, the model has been calibrated against observed groundwater heads. The hydrogeological understanding has been used to help calibrate the Compartment Flow Model, which the groundwater assessment uses to calculate water flows and water levels through the repository and the B2. Hydrogeological data is used directly to provide flows in B3 to assess the impacts of the site during the PoA.

Groundwater level data combined with information from the updated geological conceptual model [23] have been used as a basis for differentiating hydrogeological units and directions of groundwater flow around the site (see Figure 2.3 and Figure 2.4).

Groundwater level data have also been used to assess the performance of engineered barriers, inform the Engineering Performance Assessment (EPA) [12] and inform monitoring requirements during the PoA [13].

6.2 Near-field Evolution

Leachate level, quality and flow data have been used to inform the development of the near-field evolution model [6] both on the large scale and small scale. The gas monitoring and leachate data have informed the models for cellulose degradation, gas generation and source term evolution for the trenches. On the smaller scale, specific data on colloids, complexants and fluoride have been used to address specific questions on the nature and evolution of the waste.

Data on the concentrations of radionuclides and other contaminants in the leachate have been used in four ways:

- as a basis for comparison with assessment model results [14, 16, 13];
- to provide assurance that concentrations of contaminants are not in excess of some standard or do not approach that standard;
- to identify contaminants that may be released from the waste to determine whether it is necessary to monitor groundwater for those contaminants;
- for comparison with the predictions of chemical models used to predict the concentrations of certain contaminants in leachate.

6.3 Coastal Processes

The annual coastal surveys are used to:

- inform and refine coastal evolution models used in the ESC;
- monitor real-world changes in erosion, sea-level rise, and wave impacts;
- compare modelled projections with observed data to ensure assumptions remain valid.

This is essential for demonstrating long-term safety, especially given the proximity of the LLWR site to the coast and the potential for future erosion to affect waste containment.

Projections for the future evolution of the landscape in the vicinity of the LLWR were developed, with particular focus on the potential for site disruption through coastal erosion and sea-level rise. Analysis of coastal development models has resulted in estimates of cliff recession rates indicating potential timescales for facility disruption of several hundred to a few thousand years after present. Further details of this work are presented in the '*Site Evolution*' report [8].

6.4 Assessment of Impacts during the Period of Authorisation

Monitoring data provide us with an understanding of how the repository is performing and how performance has changed with time. They also enable us to carry out retrospective dose assessments. For most of our prospective dose assessments, monitoring data were used as input and scaling was applied where relevant to reflect future vault inventories. Where monitoring data could not be used, assessments were made using cautiously realistic numerical models and data from established sources. Further details of this work are presented in the '*Environmental Safety During the Period of Authorisation Assessment*' report [13].

Monitoring data were used as inputs to the assessment of impacts during the PoA as follows.

- The concentration of tritium in trench leachate and evapotranspiration rates were used in the assessment of impacts from tritiated water vapour.
- Measurements of radon gas in the trenches were used to estimate what proportion of radon generated in wastes is released from those wastes.
- Impacts from inhalation of dust and airborne particles were assessed based on data from our high-volume air sampler.
- Leachate discharge rates and concentrations were used in the assessment of impacts from discharges via the marine pipeline.
- Concentrations of radionuclides measured in the Drigg stream sediment were used in the assessment of impacts from historical permitted discharges to the Drigg stream.
- Concentrations of radionuclides measured in groundwater via off-site boreholes were used to assess impacts from the groundwater pathway.
- Radiation dose rate measurements were used to confirm the appropriateness of our numerical model of impacts from direct and scattered radiation on offsite receptors.

It is recognised that the external dose models developed for the PoA [13] currently overestimate dose compared with measurements. The potential explanations given for the difference are as follows.

- Actual disposed inventory being lower than declared inventory used in the models.
- Significant shielding effects, including grout and internal shielding within the disposal system.
- Limitations in available monitoring data, particularly:
  - Lack of spectrographic data to distinguish radionuclides.
  - Inability to separate direct vs scattered radiation in routine monitoring.

It is proposed that additional targeted monitoring is carried out to better understand the discrepancy, including:

- gamma spectrometry to distinguish Cs-137 and Co-60;
- measurements that separate direct and scattered radiation.

This should provide improved data to enable a more direct comparison between modelled and measured dose components.

6.5 Assessment of Radiological Impacts on Non-human Biota

Monitoring data and transport modelling provide inputs to the non-human biota assessment tool for different pathways of liquid and gaseous releases to the freshwater, marine, and terrestrial environments [16]. The approach ensures that the same inputs are used for both human and non-human assessments. Simple, stylised models are used for the ecosystems being assessed and for the organisms in those ecosystems. The models calculate the activity concentrations of radionuclides in different environmental media such as soil, sediment, water, and air. These concentrations are used as inputs to the internationally-recognised ERICA Tool [21] for Non-human Biota assessments. Different pathways are considered at different times and locations, including gaseous releases, liquid discharges, direct and scattered radiation, coastal erosion, and the potential release of radioactive particles. The assessment compares the calculated dose rates with a screening dose value. If the screening value is exceeded, a more detailed evaluation of the representative organisms is carried out.

6.6 Improvements since the 2011 Environmental Safety Case

The development of an integrated monitoring programme to support the 2011 ESC marked a shift in how monitoring was delivered for the LLWR. Since then, the programme has evolved significantly in response to operational needs, regulatory feedback, and technical advancements. The improvements and changes are outlined below.

Infrastructure and operational enhancements

- Existing infrastructure has been optimised, extended, or decommissioned as needed during construction phases. New infrastructure is installed where required to maintain continuity.
- Maintenance of monitoring infrastructure is now embedded within the Asset Care Programme, ensuring regular inspections and remediation efforts.
- The programme now includes enhanced leachate, surface water, groundwater, and engineered barrier performance monitoring and coastal inspections.
- A structured approach now exists for post-closure monitoring, including sealing of cap penetrations and perimeter water monitoring. BAT assessments have guided the preferred monitoring approaches.

- The MonitorPro database is used to manage and share data and GIS to visualise the findings.

Integration with ESC modelling and assessment

- Bi-annual ESC-Monitoring team meetings assess implications of monitoring data for the ESC, including breaches of assessment levels.
- Monitoring data are used to refine conceptual models and support ESC assessments, including PoA evaluations, EPA and groundwater modelling and assessment of impacts via the groundwater pathway.
- New programmes of colloid and complexants monitoring have been initiated in response to Environment Agency Forward Issues, ensuring continued validity of ESC conclusions.
- Our annual reviews assess data gaps, proportionality, and compliance with ESC objectives. Functional requirements are clearly defined and updated.

7 Future Monitoring Programme

The background, objectives and regulatory requirements of the monitoring programme are set out in Section 3. The programme is subject to annual review to ensure that all the requirements are captured and are being met and that the data collected are being examined and any trends or anomalies are investigated. It is expected that the monitoring programme will need to change over time to adapt to changes on site or to investigate specific questions or trends such as the additional groundwater monitoring being carried out for C-14.

This section sets out how we are considering long-term monitoring requirements and expected future developments. Summaries of changes required as part of repository capping programme are also presented. More details are presented in the '*Engineering Design*' report [5] and reference [104].

Arrangements for management of the site after closure during the PoA are discussed in the '*Management and Dialogue*' report [2]. The site is expected to remain in operation until 2130. The period of active institutional control, after waste disposal finishes and final closure engineering is emplaced, is expected to last for at least one hundred years. Detailed plans for the active institutional control period have not been developed but monitoring is expected to continue and provide supporting evidence to allow permit surrender. After final capping, the expectation is that leachate generation will decline significantly, with the vaults and trenches becoming effectively unsaturated [7]. Once active leachate collection ceases, monitoring of surface and groundwater systems will continue to confirm that the closure engineering is functioning as intended [13]. At the point of permit surrender all monitoring infrastructure is assumed to have been decommissioned.

As noted in Subsection 3.4, long-term monitoring refers to the monitoring that may be required at different stages of the site's operational and post-closure periods. Some of the current monitoring may continue up to the surrender of the permit. Other monitoring may only be required for a particular period or linked to a specific construction activity.

7.1 Waste Evolution

Waste evolution monitoring is intended to record changes over time as waste and site conditions evolve. It includes aspects such as biogeochemical evolution, and the potential creation of voids and subsequent settlement of the waste which results.

Direct measurements of waste degradation and evolution are not considered to be sustainable in the long term. Once the final cap is in place, such data could often be more easily acquired indirectly, if needed, through measurements of leachate levels and groundwater quality, surface water composition, gas composition and fluxes. The monitoring associated with these aspects are addressed in subsequent sections.

Monitoring of the wasteform (in trenches or vaults) can, however, be undertaken in an indirect manner. The preferred indirect methods are for settlement monitoring through measuring changes in surface level and monitoring changes in gas and leachate composition as the waste degrades.

The monitoring of vertical cap elements is considered the most appropriate way for settlement to be measured; such measurements will include differential settlement. Settlement monitoring at various levels within and underneath the cap may be undertaken.

Leachate level, flow and composition

Monitoring of leachate level and composition is required to assess the long-term evolution of the waste and to assess the performance of the interim and final cap.

Current leachate monitoring points into the trenches were primarily designed as gas vents and not for sampling leachate. The current monitoring points are dual purpose and the need for gas venting will also be considered alongside changes to the leachate monitoring. However, given the nature of the waste in the trenches and uncertainty in the exact position of the base of the trenches, constructing new monitoring points would not necessarily provide a better solution. Installations would also pose a risk to personnel during construction. Minimising the number of penetrations through the final cap is considered to be an important consideration in ensuring the cap continues to perform as required. As such, continued use of reduced number of probe holes is considered to be the BAT option [58]. Four probe holes in Trenches 1 to 6 and five in Trench 7 will be retained and extended through the final cap. The selected probe holes identified will give spatial coverage along the length of each trench

During the profile and surcharging phase, the monitoring infrastructure will be extended to the upper surface of the profile fill and covered over with a protective concrete ring and steel plate, with data logging equipment for leachate/groundwater monitoring installed and connected to a logger network for remote monitoring. It is recognised that some monitoring will need to be suspended for at least six months during the surcharging phase, which may extend beyond this timescale on some areas of the trenches. To supplement the above, selected monitoring infrastructure locations will have sacrificial loggers installed at or around the existing trench cap surface ground level. The sacrificial logger network will provide additional leachate data to supplement the monitoring information required during the surcharging phase. The arrangements for sealing around the probe holes will be considered as part of the cap constructability trial for details of which are included in the '*Engineering Design*' report [5].

Leachate composition data are used to help identify contaminants of concern that should be included in groundwater and surface water analysis to assess contaminant migration. The current infrastructure installed in the end-of-trench drains is considered to be sufficient to support long-term monitoring of leachate composition from the trenches.

As noted in Subsection 4.1.1, arrangements for leachate flow monitoring are being developed but it is assumed that flow monitoring will be required up to the point the leachate system is decommissioned.

For Vault 8, leachate flow and quality is currently measured from the pumping chambers. As part of capping, new monitoring points will be established in Vault 8. These will provide leachate levels across the vault floor and allow gas and leachate sampling. As with the trench probe holes these will need to extend through the final cap and be decommissioned before permit surrender. This arrangement is expected to be repeated in future vaults.

After the final cap is installed over the trenches, infiltration of rainwater is greatly reduced. This will lead to a gradual drying out of the trench waste, especially in regions that previously had higher water levels. For the vaults, water consumption by corrosion exceeds infiltration, so the vaults will dry out within a decade of capping [6]. The volume of leachate to be managed is expected to be minimal.

It is anticipated that there will be a move to passive drainage of Vault 8 with the construction of Vault 9a [13]. This will require changes to the flow monitoring and sampling arrangements. Future vaults will also connect to the new gravity drain with separate monitoring points for each vault.

The leachate management system, including MHT and marine pipeline, will be maintained for a period after closure, until it can be demonstrated via monitoring that they are no longer needed (i.e. that there is no significant leachate generation). This is expected to occur relatively soon (on the order of a decade) after closure; following this the leachate management system will be decommissioned. Monitoring of MHT discharges is expected to continue as a permit requirement up to the point the system is decommissioned. The leachate monitoring points, in the trenches and vaults, are expected to remain in use until permit surrender or that monitoring confirms that they are no longer required. At that point all remaining leachate monitoring points will be decommissioned and the cap penetrations sealed.

7.2 Groundwater Monitoring

Groundwater level and sampling measurements will be required throughout the operational period of the site, with some monitoring required beyond site closure into the institutional control period. Although the overall coverage is not likely to change with time, the number and position of the boreholes will change. It is recognised that as well as replacement due to degradation, boreholes will need to be replaced or modified to adapt to changes in the development of the site (capping, construction of cut-off wall, future vaults etc.). In some cases, boreholes will need to be extended to penetrate the final repository cap. The location and construction of such penetrations will require optimisation, taking account of the potential risks to barrier integrity and should be constructed and sealed to a high standard. The capping works and extension of the cut-off wall around Vault 8 will require some boreholes to be decommissioned and new monitoring points to be established. At present, boreholes are located on either side of the existing cut-off wall to assess its performance.

A phased programme of borehole extension and replacement will be required to align with the repository development programme. A programme to decommission redundant boreholes is required to ensure that the number of preferential pathways from the ground surface to groundwater is minimised.

Groundwater quality monitoring will continue to improve understanding of releases from trenches and trends with time (e.g. expectation of reduction following capping). This may include enhanced monitoring for specific radionuclides such as C-14 or to investigate unusual results.

7.3 Surface Water Flow and Quality

Surface water quality and flows around the LLWR site provide baseline information used in the assessment of engineered barrier performance (in relation to the trench cap and cut-off wall) and are used to constrain water balance calculations and models of site hydrology.

The current arrangements for stream flow monitoring across the site are considered to be adequate. As part of capping, new lagoons have been established around the site to reduce the amount of sediment run-off into surface waters during construction. The catchment areas will change over time reflecting the different cap phases and flow monitoring will need to be adapted to allow discrete water catchment areas to be defined and allow cap performance for each area to be assessed. The arrangement of the lagoons after the completion of capping of Vault 8 is shown in Figure 7.1. It is anticipated that once the final cap is completed there will only one lagoon collecting run-off from the cap as shown in Figure 7.2. Further details of the proposed arrangements are provided in the '*Engineering Design*' report [5].

Surface monitoring points and equipment will need to be maintained throughout the operational period. This may require replacement to combat asset degradation. Some monitoring points may also need to be moved or new one established to accommodate site development such as new vaults or extension of the final cap. Flow and quality monitoring is expected to continue up to permit surrender.

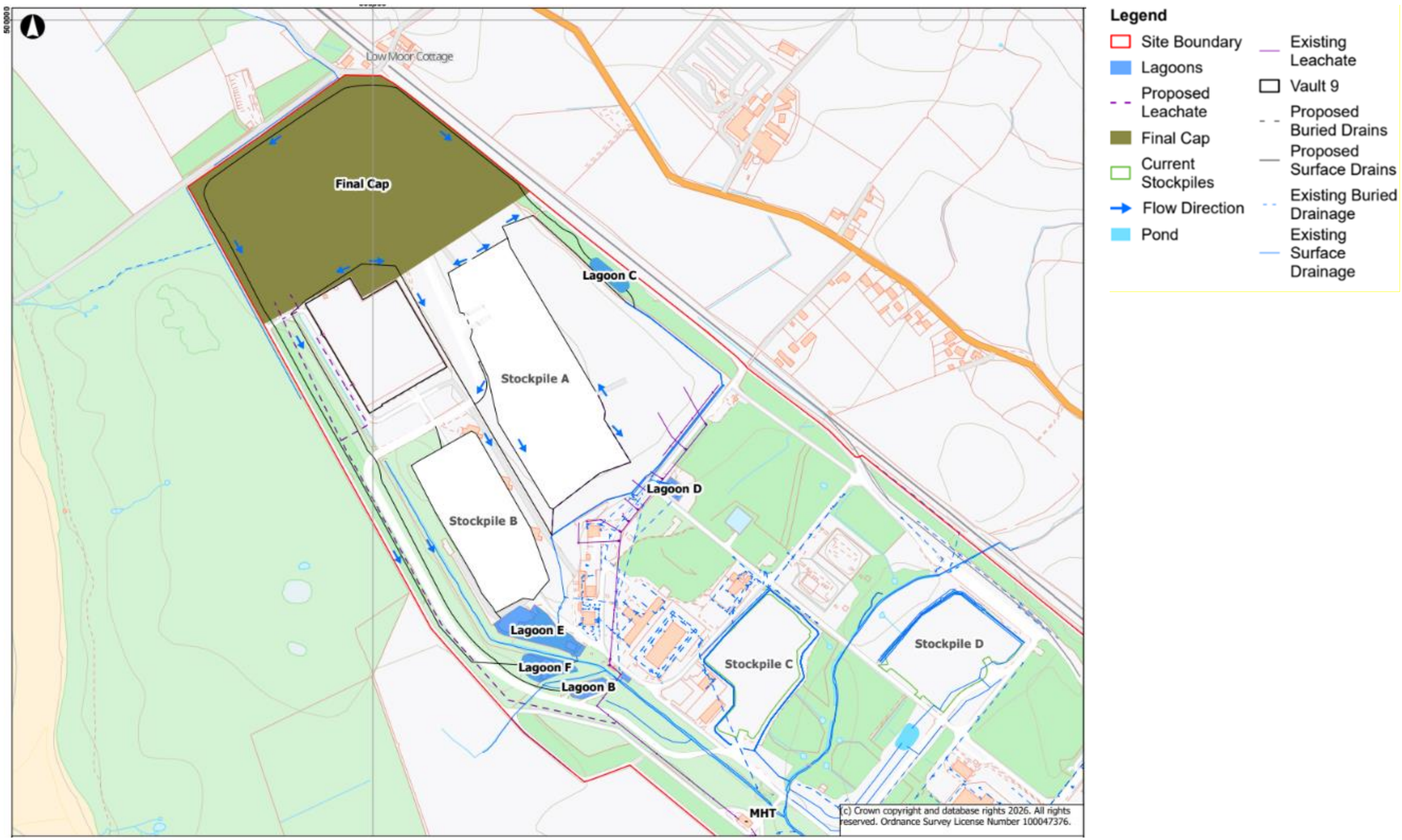


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Figure 7.1: Drainage arrangements after Vault 8 and northern part of the trenches are capped

Figure 7.2: Final cap drainage

7.4 Gas Composition and Fluxes

The gas monitoring programme at LLWR is primarily designed to monitor gas production to assess the risk of ground gases to human health. It also provides data regarding the current degradation state of cellulosic material within the waste. Changes to the gas sampling infrastructure from the probe holes is incorporated into the capping works.

In addition, the Permit requires the monitoring of gaseous discharges from active discharge stacks. These are not discharges from disposed waste and reflect the operational activities taking place on the site. It is anticipated that stack discharge monitoring will remain as an operational requirement for some buildings.

The requirement for gas monitoring is expected to be retained throughout the PoA. It is expected that leachate monitoring points will also be used as gas sampling points and will be decommissioned at permit surrender. A gas vent system is included as part of the final cap design.

The use of flux-boxes to measure the rate of gas production was discounted as we expect that too little gas is likely to be emitted. A decision was taken to focus on radionuclide gas detection using direct radiation measurements.

7.5 Container Condition

Monitoring container condition is linked to waste evolution. Container condition surveys are currently used to assess the rate of degradation/corrosion of the accessible containers. Once capped, indirect measurements will become the main method of assessing container condition.

7.6 Engineered Barrier Performance

Cap performance

Direct measurement of rate of ingress of water into the system through the cap system is not feasible without potentially compromising the integrity of the cap. Cap performance is currently assessed by calculating the water balance between water landing on the cap as rainfall and water being collected by the surface water system. This is combined with leachate level and groundwater composition data to assess whether there have been any changes in the impact of leachate. Visual and topographic surveys of the interim cap are also carried out to look for gross changes in the cap alongside settlement monitoring.

For the final cap, indirect methods of monitoring are, in the main, considered appropriate for assessing cap performance, since they would not be accompanied by any potential for damage to the cap. This is expected to include visual observations, topographic surveys and settlement monitoring both as part of construction but also long-term assessment. This would be combined with monitoring water levels in the trenches and vaults.

Observational monitoring will be implemented during construction and surcharging of the Northern Trenches and Vault 8 to provide systematic measurement of surface and sub-surface settlement and deformation, and to support construction-phase decision-making. The monitoring scheme will be designed to confirm expected engineered barrier behaviour under increasing load, to identify the magnitude and rate of settlement, and to determine when movements have sufficiently stabilised to allow progression to subsequent construction stages.

The waste in Vault 8 is containerised so is expected to behave somewhat differently than the trenches. The containers are expected to yield during construction of the cap and the hope is that the monitoring shall be able to identify this. The internal voidage within the containers shall then be expressed and the waste compressed, but the degree of settlement is difficult to predict due to the number of variables. The monitoring in the vault shall initially be limited to a trial area in which three different surcharge depths shall be trialled and the data collected continuously during surcharging and hold periods. A decision shall be made, based on this data, as to the surcharge depth to be adopted in the remainder of the vault. It is important therefore, to be able to relate the subsurface settlements to the corresponding depth of surcharge.

The monitoring system will comprise surface deformation monitoring using periodic topographical surveys (including Unmanned Aerial Vehicle photogrammetry, total station, laser scanning and GNSS[2]) and sub-surface deformation monitoring using LT-Inclibus[3] inclinometers, with rod settlement systems providing validation and redundancy. Sub-surface monitoring will be focussed on the existing trench cap, the container stacks within the Vault 8 trial area, and the vault base and walls, to capture differential settlement and deformation associated with staged profile fill and surcharging.

Monitoring data will be collected at defined frequencies during profile fill placement, staged surcharging and prescribed hold periods, with survey results and automatically logged data reviewed at regular intervals. The data will be assessed to determine settlement rates, trends and whether movements are continuing or have effectively arrested. These assessments will inform decisions on the duration of surcharging, the appropriate surcharge depth to be adopted across Vault 8, and the timing of construction of the final cap.

Monitoring data will be reviewed by the Engineering Review Panel, which will be responsible for interpreting results in the context of construction activities and for determining whether it is appropriate to proceed, extend hold periods, or implement additional controls. The observational monitoring approach will be risk-informed and adaptive, with no fixed alarm thresholds; emphasis will be placed on trend analysis, correlation with construction sequencing, and professional engineering judgement.

The observational monitoring programme will be focussed on the construction and pre-cap phases and is not intended to provide long-term post-closure performance monitoring. LT-Inclibus instrumentation will be largely sacrificial, reflecting its role in capturing critical construction-phase behaviour. Upon completion of cap construction, the monitoring results will provide a baseline for subsequent long-term monitoring undertaken as part of the operational environmental monitoring programme.

Checks on soil evolution and plant growth are also proposed using surface and sub-surface visual assessment and recording. Monitoring the soil profile would include monitoring soil accretion and loss through erosion and be linked with the assessment of sedimentation within the surface water management system. The primary weather station has been moved as part of part of the capping works and will be re-established on the final cap.

Monitoring of cap run-off combined with weather data will be used to inform water balance calculations and give an indication of cap performance in the different catchment areas. The catchment areas will change over time reflecting the different cap phases and flow monitoring will need to be adapted to allow discrete water catchment areas to be defined and allow cap performance for each area to be assessed. The sensitivity of the water balance calculations means that alternatives may have be considered to provide meaningful results. This may include monitored sections of cap with sacrificial equipment or distinct design experiments.

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[2] GNSS is a global satellite-based system that provides precise positioning, navigation, and timing information anywhere on Earth.

[3] The LT-Inclibus is an In-Place Inclinometer system designed by Sisgeo, Italy, for high-accuracy monitoring of geotechnical structures.

One of the key changes since the 2011 ESC is the improved understanding of the expected performance of the cap. The final cap at LLWR is expected to perform effectively for a prolonged period, with the geomembrane component likely to last up to or beyond 2,000 years under LLWR-type conditions as reported in the EPA [12]. The EPA included development of an updated, evidence-based understanding of the long-term performance of key system components and associated barriers. A key aspect reflected in the literature is the confidence in much longer-term geomembrane performance, compared with other applications and locations, for geomembranes within composite systems implemented in low temperature and low stress and strain situations, such as those associated with the LLWR final cap.

The EPA noted that, although certain specification requirements—most notably Oxidative Induction Time[4] and Stress Crack Resistance[5]—provide an indication of the potential for longer-term material performance, the results of these tests cannot be directly extrapolated to derive activation energy [6]. Higher Oxidative Induction Time and Stress Crack Resistance values are still considered to be desirable as indicators of confidence in longer-term performance. However, to estimate the activation energy for a geomembrane to be deployed at the LLWR, bespoke testing and analysis is likely to be required, involving time series data and immersion in waters representative of the pore fluids that the geomembrane is likely to be in contact with in the final cap.

The BAT process identified a preference for long-term monitoring of the geomembrane performance and for testing membrane samples as part of the selection process prior to installation [105]. This would help develop understanding of the performance of the cap in 'as-implemented' conditions. Here samples of the geomembrane, for example from an area of the cap outside the cut-off wall tie-in, would periodically be retrieved and tested to assess any changes in Oxidative Induction Time values and to infer changes in activation energy. In addition, these tests would help improve the baseline assumptions on performance and the data would help identify deviations from the expected evolution as set out in the ESC. These options will be considered further as part of the capping project.

Cut-off wall performance

Cut-off wall performance is assessed through analysis of groundwater levels and quality data inside and outside the cut-off wall and reported as part of the annual monitoring report. Opportunistic sampling of the cut-off wall was also undertaken when the perimeter drain was replaced.

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[4] Oxidative Induction Time is a standard laboratory test used to measure how resistant a polymer is to oxidative degradation

[5] Stress Crack Resistance is a measure of a polymer’s ability to resist environmental stress cracking—a brittle, time-dependent failure mode that occurs when HDPE is exposed to tensile stress, chemical environments, and elevated temperatures over long periods.

[6] Activation energy is the amount of energy required to initiate a chemical reaction—in geomembrane ageing, it represents the energy needed to start the oxidative degradation or crack-growth process in HDPE. For HDPE geomembranes, activation energy controls how strongly degradation rate increases with temperature.

Continued monitoring of groundwater levels and quality either side of the cut-off wall is considered to be the main option for long-term monitoring. This will require the installation of new monitoring boreholes as part of the extension of the cut-off wall. Indirect measurements of cut-off wall performance are appropriate for long-term monitoring.

Hydraulic pulse interference is considered as an option for demonstrating permeability of the cut-off wall. It is considered that the technique is best suited for either during construction or immediately post-construction. Core sampling of the cut-off wall will be considered if practical, however a process to allow representative core sampling without affecting the performance of the final cap has yet to be identified.

As with the groundwater monitoring, a phased programme of borehole extension and replacement will be required to align with capping phases and future extensions of the cut-off wall.

7.7 Reassurance Monitoring

It is expected that system performance monitoring will continue much as at present, including milk sampling, grass, high volume air sampling and perimeter dose monitoring during the operational phase of the site. This is expected to reduce after closure and cessation of active leachate monitoring but continue to some extent up to permit surrender.

7.8 Coastal Surveys

Coastal monitoring will need to continue throughout the PoA to confirm our understanding of the evolution of the coast and mechanisms involved. Currently an annual walkover over the coast is carried out to identify major changes in the coastal environment. Regular reviews of developments in climate change science and projections and review of improvements in modelling and coastal forecasting techniques are carried out as part of the ESC. Longer-term assessments demonstrate that the coast is in a state of dynamic equilibrium, with limited net change in beaches over decadal timescales. This emphasises the importance of longer-term trending, particularly in the context of rising sea-levels. As such, ten-yearly reviews of coastal erosion data are proposed.

We are contributing to the deployment of a wave rider buoy off the coast at Drigg as part of the Northwest Regional Coastal Monitoring Programme. The aim is to provide wave data to calibrate hydrodynamic models for coastal evolution projections.

Detailed monitoring of the coast immediately adjacent to the Marine Pipeline by the Engineering team will continue on a regular basis to assess when remedial measures may be required to protect the pipeline. The shoreline management plan [106] for the area shows no active intervention planned for up to 100 years allowing natural erosion of cliffs and evolution of dunes to continue.

7.9 Contaminated Land

As noted in Subsection 2.4, the Land Quality Register provides the principal method of recording our latest understanding of contaminated land. Further studies will be required to reduce uncertainty about the extent of these areas and to allow plans to be developed to allow remediation. The groundwater and surface water monitoring programme may need to be adapted to allow monitoring of specific areas in response to the findings of these investigations or to support remediation activities.

Some remediation activities are underway but others will be linked to future site development or be carried out prior to site closure. Options for managing contaminated land may also include 'disposal for a purpose' or 'disposal in situ' where a case-by-case assessment demonstrates it to be optimal. Further support to this argument is given in the ‘Optimisation and Site Development Plan’ [9] and 'Waste Management Plan' [10] reports. On-site disposal may require additional monitoring to be implemented, and this would be incorporated in the environmental monitoring programme.

8 Conclusions

Monitoring at the LLWR is currently undertaken to:

- confirm that the repository system and the wider site as a whole is not giving rise to unacceptable environmental hazards by direct measurement of the impacts and to ensure compliance with the relevant environmental standards;
- develop and build confidence in the models of the repository system by collecting data that may be used to refine conceptual models or in model parameterisation, calibration or validation;
- provide reassurance to stakeholders that the system is safe and is evolving in a manner consistent with the models and assumptions in the ESC;
- define baseline conditions before specific engineering developments or activities, such as the construction of a new repository component (for example, a vault) or the disposal of wastes at a particular location, are undertaken;
- confirm that construction activities are not giving rise to unacceptable environmental hazards by direct measurement of their impacts;
- monitor and identify any impact of land contaminated by historical operations on groundwater and surface water;
- provide information needed to support the development of a WMP and SWESC;
- work towards a programme that provides technical confirmation of the site reference state (e.g. include validation monitoring outline plans).

Environmental monitoring provides a fundamental basis for understanding the site and its evolution over time. It provides feedback on the performance of the various barriers to the release of contamination and informs the process of optimising the facility. An appropriate environmental monitoring programme, applying sound science and best practice, is vital to building confidence in successive safety assessments. Similarly, the results of successive safety assessments are used to inform the design of the monitoring programme.

The programme not only meets regulatory requirements but also adheres to best practice guidelines, ensuring that the methodology is both robust and appropriate. It is managed through a systematic approach, involving regular reviews and updates to incorporate the latest scientific and technical advancements. This dynamic management ensures that the programme remains relevant and effective in addressing emerging challenges and opportunities.

Environmental monitoring data are available from the late 1980s through to the present. This allows the longer-term trends to be identified and the effectiveness of engineered barriers assessed, indicating that the LLWR site has minimal impact on the environment and risks to the general public are negligible. The results also provide a baseline against which changes due to future operations can be assessed.

The results show the following.

- Radiological activity in groundwater and surface water has generally declined over time corresponding to the construction of the interim cap over the trenches reducing infiltration into the waste. The construction of the cut-off wall has removed the pathway from the trenches to the railway drain.
- Non-radiological monitoring shows that the LLWR is not having an adverse impact either on groundwater or on surface water as a result of historical or current activities at the site. Where non-radiological substances are detected, concentrations are generally low, consistent with natural background levels, and not localised around the LLWR site.
- The environmental risk assessment for aqueous discharge from the LLWR provides evidence that both radiological and non-radiological discharges continue to have a negligible impact on the environment.
- The impact of gas production on people and the environment is considered to be negligible for the following reasons.
    - During the 2024/25 reporting period, landfill gas production from the trench disposal area was low. The total rate of gas generation in any individual trench is low when compared with a municipal landfill facility, suggesting that the likelihood of fire is much lower.
    - There continued to be little indication of the migration of landfill gases from the disposal area to perimeter wells or buildings. Where trench cap probe holes recorded methane concentrations above background, the gas flow volumes are very low and rapid dilution of methane with the air will occur as it is released to the atmosphere.
    - Carbon-14-bearing gas emissions from the trench disposal area remain low, as evidenced by the very low gas flow rates recorded.
    - Radon gas levels across the site remain low. The majority of buildings recorded very low radon concentrations during the monitoring period.
- The calculated retrospective annual dose in 2024 was 25.0 µSv and is considered to be low in comparison with the 300 µSv requirement in the GRA and insignificant in comparison to the annual average UK dose rate due to natural background radiation.
- No evidence of the migration of contaminants from areas of known ground contamination has been identified.

During the PoA, environmental monitoring will provide assurance that the facility is performing as expected [13]. Monitoring data will provide a direct demonstration that the relevant criteria are being met and that the concentrations of any contaminants in environmental media are acceptably low. If any significant changes were observed, then appropriate action would be taken as required. The Environment Agency would be informed of any significant developments.

Environmental monitoring data are used systematically within the ESC and are particularly important in providing inputs to, and calibration data for, the 3-D groundwater flow model of the site, near-field evolution, site evolution and as a basis for comparison with assessment model results.

We recognise the need for a programme of long-term environmental monitoring that will continue throughout the PoA adapting to the needs of the site and its ESC as it develops. The monitoring programme has been modified in recent years to adapt to the capping programme. The programme will continue to require changes as new vaults are built and the site moves from operational to a fully capped and closed repository. The data collected will contribute to future updates of the ESC, which is expected to build confidence in our understanding of system performance and support permit surrender in the future.

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