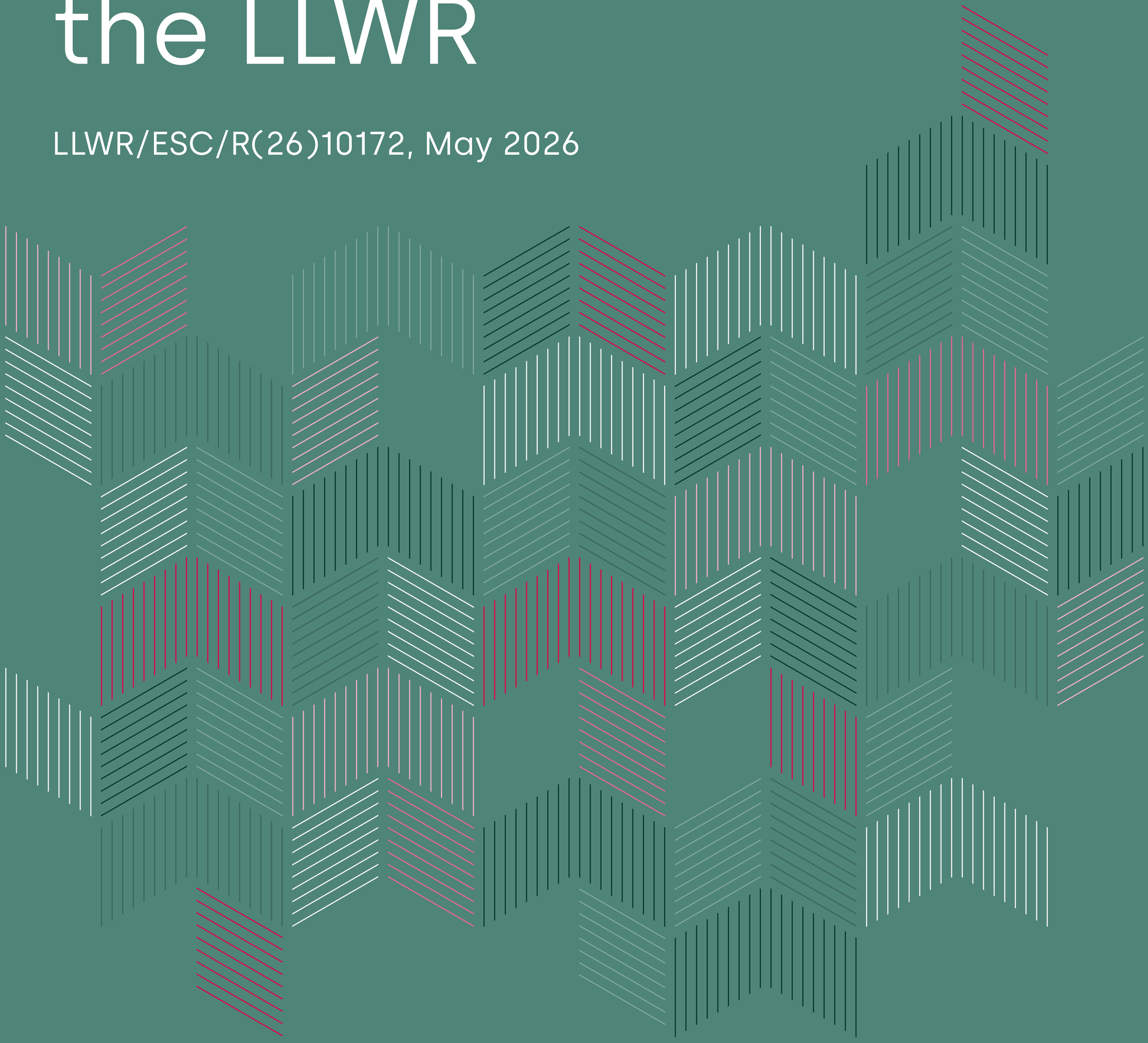
Nuclear Waste Services

HYDROGEOLOGY

2026 Environmental Safety Case for the LLWR

LLWR/ESC/R(26)10172, May 2026



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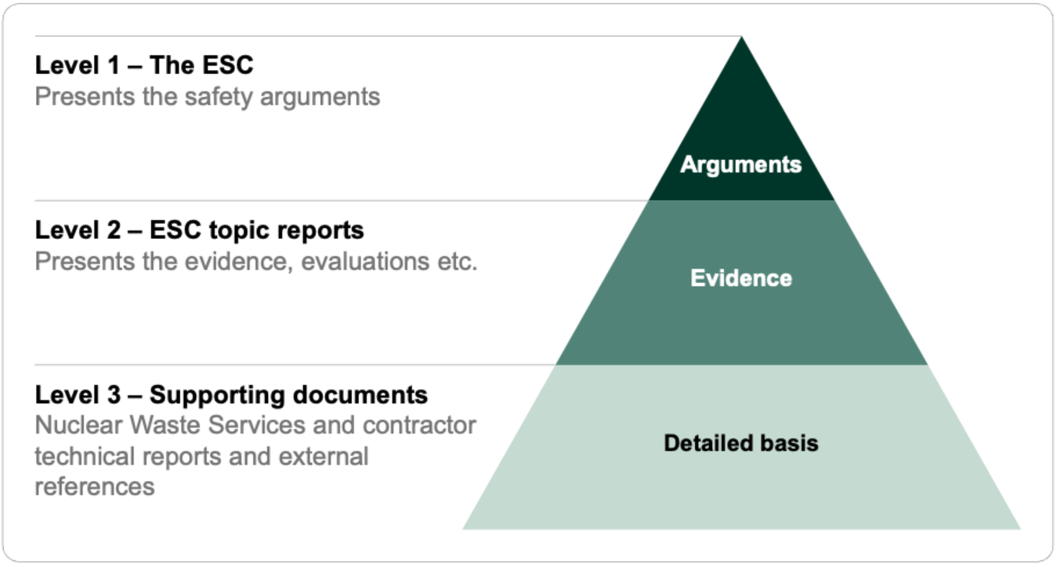
[1] In government policy, LLW is defined as radioactive waste having a radioactive content not exceeding four gigabecquerels per tonne (GBq t^{-1}) of alpha or 12 GBq t^{-1} of beta/gamma activity.

This is the Level 2 report ‘Hydrogeology’. 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 (this report)	Describes our understanding of the geology and hydrogeology of the site
Site Evolution [7]	Describes our understanding of how the site will evolve, with a focus on coastal erosion
Monitoring [8]	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 sets out the need for adequate site investigation and characterisation to provide information to support the Environmental Safety Case (ESC) and support the design and construction of the facility. The key objective of this report is to provide the relevant understanding of the geology and hydrogeology and show how this information has been used to represent groundwater flow and contaminant transport pathways within the ESC.

A comprehensive and proportionate approach to site investigation and characterisation has been implemented, as required by both the GRA and GRR. A substantially revised 3-D geological model has been produced through extensive data integration and reinterpretation. Iterative refinement has improved stratigraphic consistency across site and regional scales, enhanced spatial resolution, and enabled systematic incorporation of offshore geophysical data. The model now explicitly represents features such as channel structures and includes a significantly improved characterisation of bedrock structure and weathering. Future site investigation work will be required to support future vault developments and extension of the cut-off wall. Data acquired from these investigations will be incorporated into the geological model alongside general excavation data. The geological model will be maintained throughout the operational period and periodically reviewed to take into account any new developments in the geological understanding of the site and wider area.

The site characterisation data collected have also informed contaminated land risk assessment and the development of targeted remediation strategies, ensuring that risks to human health and the environment are properly identified and managed. The findings of the quantitative risk assessments identify that the risks from contaminated land at the LLWR are low given the current land use and management procedures that are applied. Remediation of some areas has already been undertaken and plans for further work are being developed.

The hydrogeological conceptual model has been reviewed and we have incorporated a substantial amount of new hydrogeological data into our understanding and models. This includes data from additional boreholes, updated groundwater and surface water monitoring, and new hydrogeochemical analyses. However, the core elements remain consistent with 2011 ESC. Groundwater flow is still understood to occur primarily within the Quaternary deposits and the upper part of the bedrock (mainly sandstones), down to less than 100 metres depth. It is divided into Upper and Regional Groundwater systems. The overall direction of groundwater flow in the Regional system is still from higher ground inland toward the coast, driven by the hydraulic gradient between inland recharge and sea level. The flow in the Upper Groundwater is predominantly downward. The hydrogeological conceptual model continues to recognise the strong influence of clay-rich and sand/gravel layers in the Quaternary on groundwater flow.

Combined with the 3-D geological model, the hydrogeological conceptual model has been used as a basis for the development of hydrogeological models that simulate current and future groundwater behaviour, contaminant pathways, and the impact of engineered features such as caps, cut-off walls, and vaults. The models account for the staged construction and degradation of these features, as well as future site evolution scenarios, including climate change, sea-level rise, and coastal erosion. This enables us to simulate how groundwater pathways and contaminant migration may change over time, and to demonstrate the resilience of the repository's engineering to foreseeable future changes over the next few thousand years. The hydrogeological models provide input data to the groundwater pathway assessment model. The hydrogeological conceptual model and numerical model will be maintained so that they are available to support future assessment and allow specific queries to be investigated. This will include the review of surface water and groundwater monitoring data to evaluate the impact of site developments such as capping or cut-off wall construction on the hydrogeological setting and to confirm that the conceptual model remains valid.

We have undertaken work to assess the effects of hydrogeological uncertainties at the LLWR site, including in bulk permeabilities; heterogeneity; bedrock faulting; offshore and internal structure of the confining unit; near-surface and recharge variability; and saline intrusion. Whilst there are variations in flow paths associated with these uncertainties, we can demonstrate that the overall pattern of flow is unaffected and that the representation of the groundwater pathway in the safety assessment is robust.

The LLWR site is well characterised in terms of its geological and hydrogeological setting. The models developed provide a sound basis for safety assessments and facility performance evaluations and are supported by a comprehensive data collection and monitoring programme. The iterative approach to site investigation, model refinement, and uncertainty analysis ensures that the ESC remains fit for purpose as knowledge and site conditions evolve. The ongoing programme of data collection, monitoring, and model development will continue to inform future assessments and support safe management of the LLWR.

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1 Introduction

1.1 Objectives

The key objective of this report is to provide the relevant understanding of the geology and hydrogeology and show how this information has been used to represent groundwater flow and contaminant transport pathways within the ESC. The work presented in this report also underpins the development of conceptual models for the physical and chemical evolution of the near field and provides direct inputs to the assessment models used within the ESC.

1.2 Relevant Regulatory Guidance

The LLWR is regulated by the Environment Agency under Schedule 23 of the Environmental Permitting (England and Wales) Regulations 2016 (EPR 2016). Submission of the ESC is a requirement of the site's Permit. Guidance on the specific regulatory requirements relevant to near-surface disposal of solid radioactive waste is set out in the environment agencies' '*Near-surface Disposal Facilities on Land for Solid Radioactive Wastes: Guidance on Requirements for Authorisation*' (the GRA) [19]. Requirement R11 of the GRA sets out the need for adequate site investigation and characterisation to support the ESC. The box below reproduces the key relevant paragraphs from the GRA.

> **Requirement R11: Site investigation**
>
> 6.4.6 The developer/operator of a disposal facility for solid radioactive waste should carry out a programme of site investigation and site characterisation to provide information for the environmental safety case and to support facility design and construction.
>
> 6.4.7 The length, complexity and detail of the site investigation need to be appropriate for the information requirements of the environmental safety case which, in turn, should be proportionate to the hazard presented by the waste to be disposed of. The developer/operator should establish a proportionate approach to site investigation that uses some or all of the results from site characterisation, modelling studies, design and construction to guide investigations. The site investigation should be presented as part of a structured programme that provides the requisite information for the environmental safety case.
>
> 6.4.8 The developer/operator will need to show that the geological environment is characterised, understood and can be analysed to the extent necessary to support the environmental safety case. This will involve considering, for example, the lithology, the stratigraphy, the geochemistry, the local and regional hydrogeology, and the resource potential of the area. Where appropriate, the developer/operator will also need to assess the potential for, and effects of, dynamic processes that are significant to the environmental safety case.

6.4.10 The developer/operator should show that the geological, hydrogeological and other characteristics of the region and the site under present and reasonably foreseeable future conditions will allow the environmental safety case for the facility to be made. This demonstration should include considering features and properties of the site related to the release and transport of radionuclides in the gas phase.

6.4.11 The developer/operator should identify the presence of any actually or potentially valuable resources near the site and make an assessment of the extent to which the site and its surroundings might be disturbed as a result. The developer/operator will need to consider the implications for the integrity of the disposal system (see Requirement R7).

6.4.13 Before carrying out any intrusive geological investigations, the developer/operator should assess the extent to which these might disturb the site and any implications this might have for the environmental safety case.

6.4.14 Site characterisation should involve investigating specific properties of the site and its surroundings in sufficient detail to support the environmental safety case and may include the following:

- Local and regional borehole investigations;
- Characterisation of soil layers and Quaternary deposits;
- Characterisation of surface waters and sediments;
- Characterisation of surface and sub-surface flora, fauna and ecosystems;
- Development of regional and local geological, geotechnical, hydrogeological and geochemical understanding;
- Description of the environmental baseline prior to facility construction activities.

6.4.15 Depending on the hazard presented by the waste to be disposed of, the developer may need to adopt an iterative approach to facility design and development of the environmental safety case as results are progressively obtained from the site characterisation activities. This will include a growing understanding of the capability of the proposed facility in terms of the types and quantities of waste it will be able to receive. As the environmental safety case is developed, it will help to guide what further site characterisation activities are needed.

The GRA describes the need for a site investigation programme that is appropriate for the information requirements of the ESC and is proportionate to the hazards, both radiological and non-radiological, presented by the waste. The GRA is not prescriptive in its requirements for site investigation but suggests that consideration should be given to the lithology, the stratigraphy, the geochemistry, the local and regional hydrogeology, and the resource potential of the area. The potential for, and effects of, dynamic processes that are significant to the ESC should also be considered. The GRA also accepts that knowledge of site characteristics is expected to increase progressively through the site investigation and the facility development phases.

This report also contributes to addressing the environment agencies' '*Management of Radioactive Waste from Decommissioning of Nuclear Sites: Guidance on Requirements for Release from Radioactive Substances Regulation*' (the GRR) Requirement R8: Site characterisation and monitoring [20]. The box below sets out some of the key paragraphs from the GRR.

Requirement R8: Site characterisation and monitoring

A4.12 Operators should carry out a programme of site characterisation and monitoring to provide information needed to support the WMP and SWESC. The programme shall include appropriate validation monitoring to provide technical confirmation that progress towards the site reference state is as expected or to validate that the site reference state has been achieved.

A4.13 Site characterisation and monitoring should be suited to the information requirements of the SWESC and should be presented as part of a well-structured programme that provides the requisite information. Operators should establish a proportionate approach to site characterisation and monitoring that uses appropriate assessments to guide further investigations, taking into account the nature of operations and former operations on-site.

A4.14 Site characterisation and monitoring should establish, in sufficient detail:

- the geological properties of the site, including the lithology, the stratigraphy, the geochemistry and the local and regional hydrogeology the potential for, and effects of, dynamic geological processes that may be significant to the SWESC
- the resource potential of the area under and near the site so as to assess the extent to which the site and its surroundings might in future be disturbed through exploitation of the resources the nature, magnitude and distribution of the radiological hazards remaining on or adjacent to a site
- the nature, magnitude and distribution of any non-radiological hazards associated with, or potentially interacting with, the radiological hazards past and present rates of movement and diffusion of these hazards, if for example transported by groundwater, so that extrapolations can be made into the future
- uncertainties in each of the above

A4.15 The site characterisation programme should also gather sufficient information to provide estimates of background radioactivity present at the site. This will include radioactivity of natural origin, together with that of human origin such as from

> weapons testing, from historic authorised discharges and from any local or remote nuclear accidents.
>
> A4.17 Knowledge of the site characteristics relevant to the SWESC is expected to increase progressively with time. We shall be proportionate in our assessment of the adequacy of the site characterisation and monitoring information presented in the context of an evolving SWESC.

The GRR is not prescriptive in its requirements and there is significant overlap between the site characterisation required by the GRA and what is required by the GRR. Site characterisation is essential to understand the nature and extent of radioactive contamination and supports decisions about remediation, waste management, and ultimately the release of the site from regulatory control. This report provides details of some of the work carried out to understand the extent of contamination on the site and understand future waste management requirements.

1.3 Scope

Understanding the geological and hydrogeological setting of the LLWR site is fundamental in being able to represent the behaviour of the site and its future evolution, and the performance of engineered barriers in the safety assessment.

The scope of this report includes:

- description of the geographical setting;
- description of the site investigation programme and the development of the geological understanding since 2011;
- description of the geology of the LLWR site and surrounding region;
- description of the hydrogeological setting and the available hydrogeological and hydrogeochemical data;
- presentation of the hydrogeological conceptual model for the site and likely evolution of the site;
- description of the investigations carried out into contaminated land and their findings;
- demonstration of how the supporting hydrogeological models have been developed and how the hydrogeological system is effectively represented in the safety assessments.

The report is supported by data and arguments presented in other ESC reports:

- The ‘*Site History and Description*’ report [3] provides details of the site history.
- The chemical evolution of the site, including gas generation and migration is covered in the ‘*Near Field*’ report [6].

- The '*Site Evolution*' report [7] provides the detailed analysis of the coastal system and expected evolution of this system.
- The '*Monitoring*' report [8] provides details of the monitoring programme that has been utilised to supply the underpinning hydrogeological data.
- Assessments of the radiological and non-radiological impacts of the LLWR during the Period of Authorisation (PoA) to people and non-human biota are based on conceptual models developed from site characterisation data. Models used to estimate impacts at later times have also been based, in part, on an understanding of the likely evolution of the site. This is discussed in the '*Environmental Safety during the Period of Authorisation*' report [13], the *'Assessment of Long-term Radiological Impacts'* report [14] and the '*Assessment of Impacts on Non-human Biota*' report [16].

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

1.4 Structure

This report is structured as follows.

- Section 2 provides background information on the site, the development of the site investigation programme, and the approach to provide information for the ESC and to support facility design and construction.
- Section 3 gives the geological understanding of the site at both the regional and site scale. This section also shows how the geological understanding has been used to develop a 3-D geological model for the site, which provides a framework for the hydrogeological modelling.
- Section 4 defines the hydrogeological setting by presenting the available hydrogeological data, the development of the hydrogeological conceptual model and the expected site evolution.
- Section 5 explains how the hydrogeological models have been developed to support the ESC, the process of model calibration and the predicted groundwater pathways. This section shows how the hydrogeological models have been used to investigate and to represent the evolution of the natural environment and the repository engineering. The section also considers uncertainties in the hydrogeological interpretation.
- Section 6 provides a summary of the key findings of the site investigation programme and highlights how the understanding has developed since the 2011 ESC.

The report pulls together the substantial amount of work that has been done since the 2011 ESC. Due to the large volume of supporting work, it is not feasible to replicate all the detail of the supporting references. For more detail, the reader is directed to the following key supporting documents: the geological conceptual model report [21], the geological modelling report [22], the hydrogeological conceptual model report [23] and the hydrogeological modelling report [24].

Gas generation and transport processes in the near field are addressed in the '*Near Field*' report [6].

Information on the characterisation of surface and sub-surface flora, fauna and ecosystems is covered as part of the '*Non-human Biota*' report [16].

2 Background and Approach

2.1 Site Setting

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 towards the coast. The River Esk is separated from the other rivers by the prominent ridge of Muncaster Fell, as shown in Figure 2.1.

The site occupies an area of approximately 100 ha, of which approximately 40 ha form the existing waste disposal area, see Figure 2.2. 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 to the east, initially gradually but then steeply, to be dominated by the Lakeland fells.

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 [7] 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 scenario of future site evolution is considered to be progressive disruption of the LLWR site by undercutting of its engineered structures within a timeframe of several hundreds to a few thousand years. The '*Site Evolution*' report [7] 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 south-western boundary, the site borders a Site of Special Scientific Interest (SSSI). The site is principally surrounded by grazing land.

Photographic and map evidence suggests that the principal use of the area, prior to the site being used as a Royal Ordnance Factory (ROF), was for agriculture. Manufacture of the explosive trinitrotoluene (TNT) began at the site in 1941 and continued until 1945. Subsequent to the conclusion of World War II, the site was also used as an area for munitions decommissioning [25]. 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 history and full description are provided in the '*Site History and Description*' report [3].

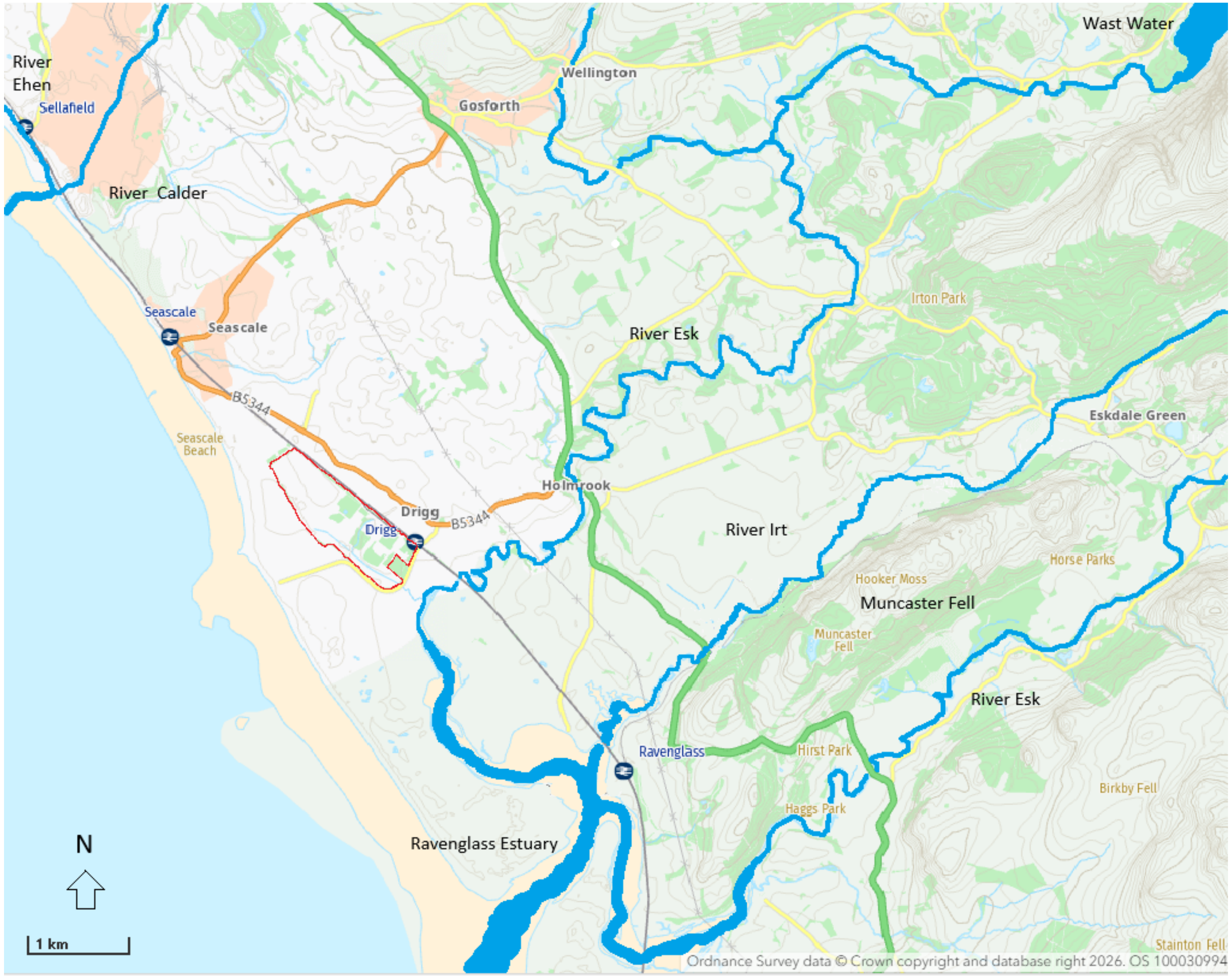


Figure 2.1: The region around the LLWR showing local rivers

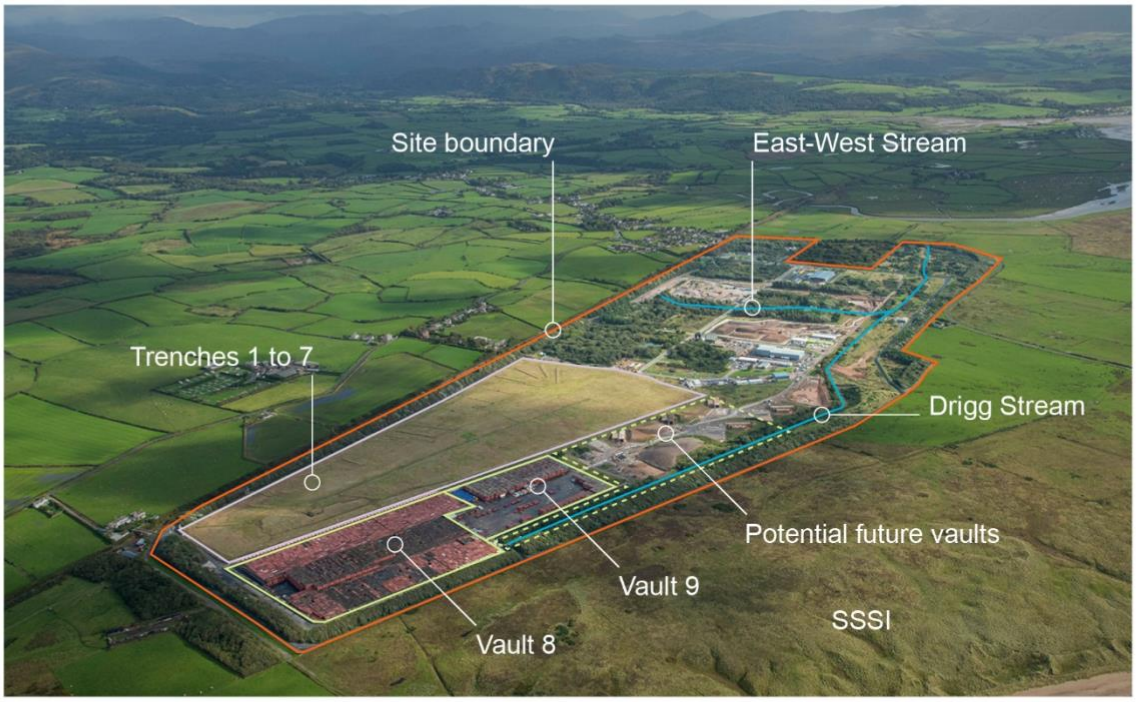


Figure 2.2: Key features of the LLWR

The site has been in operation as a LLW disposal facility since 1959. Wastes were originally disposed by loose tipping into a series of trenches (1 to 7, see Figure 2.2). Trench 1 was originally a railway cutting constructed as part of the ROF, cut into the natural clay. Subsequent trenches were cut deeper using the natural clay to provide containment. Where clay was not present bentonite-enriched sand was rotavated into the base.

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. Replacement of an interim membrane over the southern part of the trenches commenced in 2025.

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. Details of the engineering are provided in the *'Engineering Design'* report [5].

Disposals of containerised waste to Vault 8 commenced in 1988, with disposals to Trench 7 ceasing in 1995. Vault 8 has a concrete slab base with both surface and subsurface engineered drainage systems to control water flow and minimise leachate build-up. The under-slab drainage system is underlain by at least 1 m of natural clay, with hydraulic conductivity not exceeding $1\ 10^{-9}$ m s^{-1}. During construction, the natural clay was found to be intermittent or missing in places. Consequently, bentonite-enriched sand was installed to provide the necessary low-permeability layer. Vault 8 has reinforced concrete retaining walls, supported in places by secant pile walls. These walls form the vertical containment boundary of the vault and tie into the basal engineered layers.

Vault 9 construction was completed in 2010. Vault 9 sits on a double composite basal liner, comprising two 500 mm thick bentonite-enriched sand layers with hydraulic conductivity not exceeding 1 10^{-10} m s^{-1}, 2 mm thick High-Density Polyethylene (HDPE) geomembranes, and an intervening leak-detection drainage layer. The basal liner is designed to provide very low permeability, long-term infiltration control beneath the vault floor. A concrete running surface is in place over the basal liner, which allows water to be captured in the leachate collection system. The perimeter west and internal north walls are double-leaf reinforced concrete walls, each 350 mm thick, separated by 1 m or more of infill, including bentonite enhanced sand. The 2 mm thick HDPE geomembrane is also extended up the inside wall here, in continuity with the basal liner system. The east wall is similar, but with the reinforced concrete secant pile wall providing the outer wall.

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. Future vaults will have a similar design to Vault 9 but with a single composite liner system. This is considered to be sufficient due to improved understanding of infiltration and the performance of the final engineered cap.

Once the vaults are filled, a multi-layer final cap will be placed over the trenches and vaults. It is anticipated that this will be done progressively as vaults are filled. 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. Construction of the final cap over Vault 8 and the northern part of the trenches is expected to commence in 2029.

The final cap is designed to:

- restrict water infiltration and encourage run-off;
- isolate and protect the waste from intrusion and erosion;
- control the 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;
- perform passively without maintenance after the Period of Authorisation.

The cut-off wall will also be extended around the disposal area as the cap is progressively installed. The proposed extension will be constructed to 2 m below the bottom of the vaults, to ensure it extends below the sub-vault drainage blanket. 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 Site Investigation Programme

Site investigation programmes have been carried out at the LLWR to provide information for the ESC and to support facility design and construction. By understanding how the natural system works, it is possible to determine how the engineered structures constructed for waste disposal will interact with the surrounding environment, and to assess the potential migration of contaminants from the site. The importance of site characterisation has increased since 1959, as has the requirement to be able to demonstrate the long-term safety of the site. The site investigation process has been iterative, with each phase adding to the previous dataset. Only limited site investigation was carried out when waste disposal commenced, therefore, the baseline environmental conditions can only be inferred from studies of the surrounding area. The environmental monitoring programme is part of the ongoing site investigation programme providing groundwater and surface water data to inform the hydrogeological setting. More details on the monitoring programme are provided in the '*Monitoring*' report [8].

The site has been subject to a series of intrusive (trial pits, boreholes, Cone Penetration Tests (CPT), logging of beach cliff exposures and other excavations, hydrogeological testing and environmental sampling) and non-intrusive investigations (geophysics, bathymetry surveys, Light Detection and Ranging (LiDAR) surveys, satellite imagery and aerial photography), some of which date back to 1939, when the site was being developed as a ROF. Since then, approximately 700 boreholes have been drilled within and in close proximity to the LLWR site. The site investigations have usually preceded major construction work, such as vault construction, providing geological and geotechnical data to support design or to expand the coverage of groundwater monitoring. Excavations for construction work are also used to gather information on the ground conditions. Further details of the site investigations and data used to develop the geological conceptual model is provided in Section 3.

The Drigg Site Characterisation Programme (DSCP) was instigated to provide a focused investigation of the site ahead of the 2002 Post-closure Safety Case (PCSC) [26]. This involved drilling a network of 41 boreholes on site and eight boreholes off site in the first phase of work, followed by clusters of between two and four closely spaced boreholes drilled to different depths at twelve locations on site (the C1 to C12 cluster borehole sets). Various geophysical surveys (resistivity, tomography and seismic reflection) were also undertaken. The work was presented in the '*Geological Interpretation*' report of the 2002 PCSC [27].

The Environment Agency review of the 2002 PCSC [28] recognised that Drigg Site Characterisation Programme provided a much more detailed and improved geological and hydrogeological understanding of the site. However, the review also commented that the improved understanding of the site emphasised the potential significance of remaining uncertainties. The following deficiencies were identified.

- A lack of information on flow paths between the LLWR and the coast. Insufficient data have been collected to evaluate with confidence the potential presence and geometry of flow paths between the LLWR and the coast. Several such pathways are simply rated as uncertain to occur by BNFL.

- A lack of reliable data on hydraulic conductivities and water fluxes in the shallow and deep drift units between the LLWR and the coast.
- A lack of information on the hydrogeological characteristics of the Ormskirk Sandstone beneath the LLWR and between the LLWR and the coast.
- A lack of information on the spatial distribution of potentially significant hydrogeological features (e.g. glaciotectonic features).
- A lack of information on the location of the saline interface to the west of the LLWR.

Following the review, a further programme of site investigation was instigated to try and address the uncertainties. Between 2004 and 2007, 77 boreholes and 17 trial pits were constructed both on site and off site [29] to support the design and construction of Vault 9. The boreholes provided information on the Quaternary deposits and the underlying Ormskirk Sandstone. A further 14 boreholes were constructed in 2009 [30] to provide more information on the geology and hydrogeology between the site and coast. These data were incorporated into the updated geological understanding of the site [31] and presented in the 2011 ESC [32]. The Environment Agency review of the site understanding in 2011 ESC [33] concluded that

> *'The area in and around the LLWR has been extensively investigated. The current level of site understanding can be considered as well established. However, the heterogeneous nature of the Quaternary deposits underlying and adjacent to the LLWR means that precise characterisation of the layout of low and high permeability lithologies may not be achievable. We consider that LLW Repository Ltd's interpretation and modelling of the Quaternary geology and hydrogeology is appropriate, but note that there will always remain a level of uncertainty over the behaviour of groundwater within these geologies at a small scale (10's to 100 metres).'*

No specific site investigation plans were proposed as part of the 2011 ESC but it was noted that further characterisation would be required to support construction activities. Since 2011, the main construction activities have primarily been associated with preparation for capping. The associated excavations have provided further information on the shallow geology around the site but have also contributed to our understanding of the contaminated land associated with the use of the site for TNT production, the storage of radioactive waste prior to disposal and contamination associated with disposal operations.

In 2019, we were asked by the NDA to consider the potential for hosting a new near-surface disposal facility at the LLWR site to dispose of some of the United Kingdom's less-hazardous Intermediate Level Waste. This facility could have involved the disposal of waste at greater depths than in the LLWR vaults. As part of this work, we undertook non-intrusive and intrusive work to gather geological, geotechnical and hydrogeological data to inform siting and design decisions for future engineered disposal structures, including silo-type facilities. This included the construction of 18 boreholes to a depth of up to 120 m below ground level and the establishment of groundwater monitoring points in 2021. The new facility programme was not taken forward but the data have been useful and have been incorporated into the geological model for the site and used to inform the development of the hydrogeological conceptual model.

Understanding the regional geological setting is important for development of the geological conceptual model. We have included data from previous Nirex site investigation programmes carried out in West Cumbria in the 1990s to support the Geological Disposal Facility [34, 35], site investigation at Sellafield [36], for the proposed nuclear power station at Moorside (north of Sellafield) [37] and off-shore data relating to oil and gas exploration or more recently data collected. Some data from the more recent Geological Disposal Facility investigation work for Mid and South Copeland have been used but it is noted that the work predates the completion of the NWS Site Descriptive Model v1.0. As a result, the understanding of the geological succession and some of the interpretations may differ in detail.

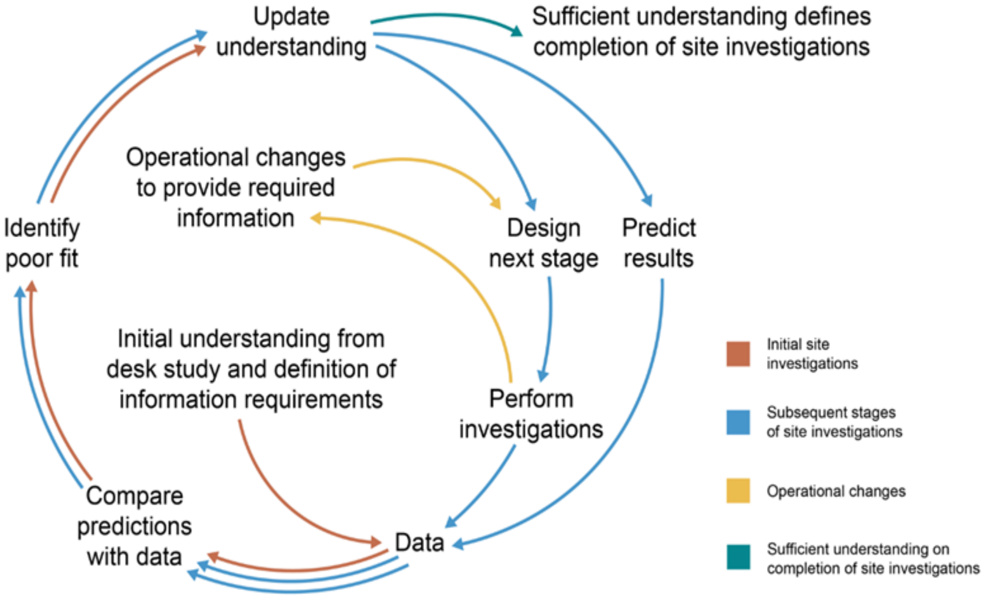


Figure 2.3: **The lifecycle of a site investigation project showing the interactions among components of the iterative loops that need to be established as part of a site investigation project for the provision of data and understanding and the identification of remaining uncertainties and knowledge gaps [38]**

We continue to collect data and incorporate data as they become available. This also includes taking into account any developments in the geological understanding from the wider region. We expect that future investigation work will be required to support future vault developments and extension of the cut-off wall. We also recognise that learning from site investigations is iterative, as illustrated by Figure 2.3, and that site-related requirements are likely to evolve in response to safety case development (more detail and additional information might be required). The groundwater monitoring network [8] may need to be extended in response to construction of future vaults, and to provide further information to support the hydrogeological conceptual model or investigate unusual monitoring data. Any future investigations will be planned to minimise any potential disturbance of the disposals and any implication this may have for the safety case.

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.

2.3 Delivery Approach

Since the delivery of the 2011 ESC, we have carried out a programme of work to improve our geological and hydrogeological understanding. This enabled a significant update of our geological and hydrogeological models in 2020, together with a detailed plan for analysing and quantifying uncertainty in the models. The site investigations between 2020 and 2021 resulted in a large quantity of additional geological and hydrogeological data, which have been incorporated into the understanding and hence into the models. The site investigation specifically targeted the sandstone bedrock where there was previously limited information available.

Our programme included the following.

- Development of the latest geological understanding through an integrated programme of intrusive and non-intrusive investigations, supported by reinterpretation of legacy data, specialist analytical techniques, and development of an updated conceptual and 3-D geological model to represent complex Quaternary and bedrock geology [21].
- Development of the hydrogeological conceptual model [23] to reflect the updated geological understanding, hydrogeological testing results and monitoring observations.
- Development of hydrogeological models [24] that simulate current and future groundwater behaviour, contaminant pathways, and the impact of engineered features such as caps, cut-off walls, and vaults to provide an overall representation of the movement of groundwater that can be used in the safety assessment calculations.

- Undertaking work to assess the consequence of hydrogeological uncertainties at the LLWR site, including bulk permeabilities, heterogeneity, bedrock faulting, the extent of the specific controlling units, recharge variability and saline intrusion [39]. We have assessed the potential uncertainties in bulk groundwater flow rates through the aquifer on the basis of these uncertainties.
- Development of 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 [7].

The programme has focused on areas that are considered to be important for the assessment of the groundwater pathway in understanding how water will interact with the repository, how contaminants may be released and what the potential receptors may be.

By understanding how the groundwater behaves in the current environment, we are able to understand how groundwater pathways may be affected in future due to site developments (future vaults, engineering degradation, capping etc), climate change, sea-level rise and coastal erosion.

3 Geological Understanding

This section provides the geological understanding on both the regional and site scale. The section also shows how the geological understanding has been used to develop a 3-D geological model for the site that can be used as the framework for the hydrogeological modelling. This section summarises the work presented in the geological conceptual model report [21] and the geological modelling report [22].

3.1 Geological Conceptual Model

The geological conceptual model defines which geological units exist, their geometry, and connectivity, which is then used as the basis for the hydrogeological models, helps identify potential pathways for contaminant migration and informs engineered barrier design.

3.1.1 Development of the Site Geological Conceptual Model for Quaternary Geology

The regional geology of West Cumbria is described in the publications of the British Geological Survey (BGS) [40, 41]. The geology of the region can be summarised as consisting of thick (up to 70 m) Quaternary age (last 2.6 million years) deposits overlying bedrock. However, this description does not reflect the complexity of the geology of the region and the sequence of events and that can only be interpreted by what is visible at the surface and evidence from intrusive and non-intrusive investigations. The BGS regional guide for Northern England [21] notes that:

> *‘The sequence of events that occurred during the MLD [Main Late Devensian] glaciation is not fully understood since there is insufficient geochronological control. Some phenomena result from more than one phase of glaciation and the stratigraphical record is beset with difficulties of regional correlation.’*

A series of geological conceptual models have been developed for the site. The 1988 '*Assessment of the Radiological Impact of Disposal of Solid Radioactive Waste at Drigg*' [42] noted that:

> *'…the geology of Drigg site is not simple.*'

The site is reported as being covered by 12 to 45 m of glacial and post-glacial deposits, layers of tills (boulder clays), moraines and outwash sediments. These overlie a thicker bedrock of St Bees Sandstone. The glacial deposits were characterised into eight separate layers, although the characteristics of each layer are variable across the site, and some layers are absent in parts of the site. Some layers had significant clay and were of relatively low permeability. The intervening layers were described as having higher permeability and were referred to as aquifers.

For the 2002 PCSC [43], the geological conceptual model was built through an iterative process: initial models (from 1988, 1993 and 2000) were refined using new data from the

Drigg Site Characterisation Programme. The geological interpretation used an event stratigraphy approach to describe the Quaternary deposits, using features such as the interpreted advances and retreats of the margins of the Irish Sea ice sheet to differentiate the deposits. The approach made significant assumptions when assigning such processes and events to the resulting individual layers of sediment and also when identifying the boundaries between the layers and correlating these layers between borehole logs. For the 2002 PCSC, the BGS event stratigraphy was adopted as the framework, but a site-specific set of units were defined, which were different from the BGS lithostratigraphical units. This event stratigraphy approach for the LLWR site produced units that could not be confidently correlated across the site, nor with the BGS lithostratigraphical units, and which did not have well-defined material properties. The 2002 PCSC geological interpretation was also criticised as not providing a suitable basis for the hydrogeological interpretation, because it focused on describing the geological history rather than on describing the spatial distribution of materials, as needed to underpin the hydrogeological interpretation [44].

The geological understanding for the 2011 ESC is captured in reference [31]. It summarises the three main approaches taken for characterising the Quaternary deposits at the LLWR. These were: an ‘events-based stratigraphy’ of BNFL from 2002, a regional lithostratigraphy of the BGS and Nirex from a similar time, and the ‘lithofacies’ approach. All of these approaches were ‘modelled’ using 2-D geological cross-sections interpreted primarily from borehole data. The interpreted elevation of geological boundaries along the cross-sections was then extracted and applied to a digital 3-D surface to provide an input to 3-D hydrogeological models. This was referred to as explicit modelling. The lithofacies approach placed more emphasis upon descriptive analysis of the sedimentary materials and fewer assumptions and inferences were made regarding the processes and events that may have formed them. This allowed lithofacies units (a mappable subdivision of a stratigraphic unit that can be distinguished by its facies or lithology − the texture, mineralogy, grain size, and the depositional environment that produced it) to be defined in terms of lithological assemblages to which hydrogeological properties could reasonably and consistently be ascribed. A lithofacies approach was used to correlate units with similar material properties. The lithofacies were not constrained by time of formation, could cut across one another and could be discontinuous. This approach '*avoids the problems related to a requirement to determine the stratigraphy of the sediments as an initial and main purpose of the study*' [31]. Materials with shared lithological characteristics, were assumed to have similar shared bulk hydrogeological properties.

The previous approaches to model development are representative of the geological understanding, computational possibilities, and data that were available when these approaches were applied. In the last decade, geological understanding has improved, computational capability to produce digital models has significantly advanced, and additional data have become available. The approach used to produce geological models has evolved accordingly.

Since the 2011 ESC, significant work has been undertaken to continue the development of the geological conceptual model. The process begins with the development of a regional geological framework, informed by published literature and previous studies on glaciation, deglaciation, and coastal evolution in West Cumbria. This regional understanding provides the boundary conditions and geological context within which site-specific data can be interpreted.

This work has been undertaken in conjunction with the acquisition of new data (boreholes, geophysics, cliff logs, LiDAR and bathymetry), reassessment of legacy data (historical boreholes, Cone Penetration Test data and reinterpretation of excavation logs) and the use of micropaleontology and dating. The current approach combines lithofacies and event-based stratigraphy. This ensures that units with similar material properties are grouped for representative bulk permeability. A 'landsystem' and event stratigraphy approach is also applied, which captures complex geometries typical of glacial deposits, considering depositional environment and deformation history [45, 46, 47]. It also incorporates sequence stratigraphy where relative sea-level changes dominate deposition. This means that units share bulk material properties and geological history, improving predictive geological modelling.

The landsystem approach uses patterns of glacial landforms and associated sediments to reconstruct former ice margins and understand glaciation style. By analysing sediment-landform assemblages and comparing them with modern analogues, it helps identify ice extent and depositional environments. Combining geomorphological evidence (e.g. moraines) with sedimentological data provides a robust basis for interpreting past glacial events, improving reconstructions beyond earlier work that relied mainly on sediment data.

The geological conceptual model for the LLWR has been developed through an iterative process in which regional geological understanding and successive site-specific datasets have been repeatedly integrated, interpreted, tested and refined. Legacy information and new investigation data have been compiled and assessed within a regional framework of glacial, depositional and erosional processes, leading to the development of an event-based stratigraphic concept for the Quaternary sequence. Geological judgement has then been applied to interpret unit geometry, continuity and relationships where data are limited or ambiguous, and this conceptual understanding is implemented in a 3-D geological model. The act of model construction provides a check on conceptual consistency and highlights areas requiring further refinement, prompting iteration. Each model update has been compared explicitly with earlier conceptual models to understand what has changed and why, and uncertainties have been identified and documented throughout the process.

3.1.2 Bedrock

The bedrock geology of the area is characterised by a mix of sedimentary, and extrusive and intrusive igneous rocks, as shown in Figure 3.1. The oldest rocks within the area of interest near to the LLWR site are found on the eastern side of the district and belong to the Borrowdale Volcanic Group (BVG) which, in West Cumbria, consists mainly of volcanic

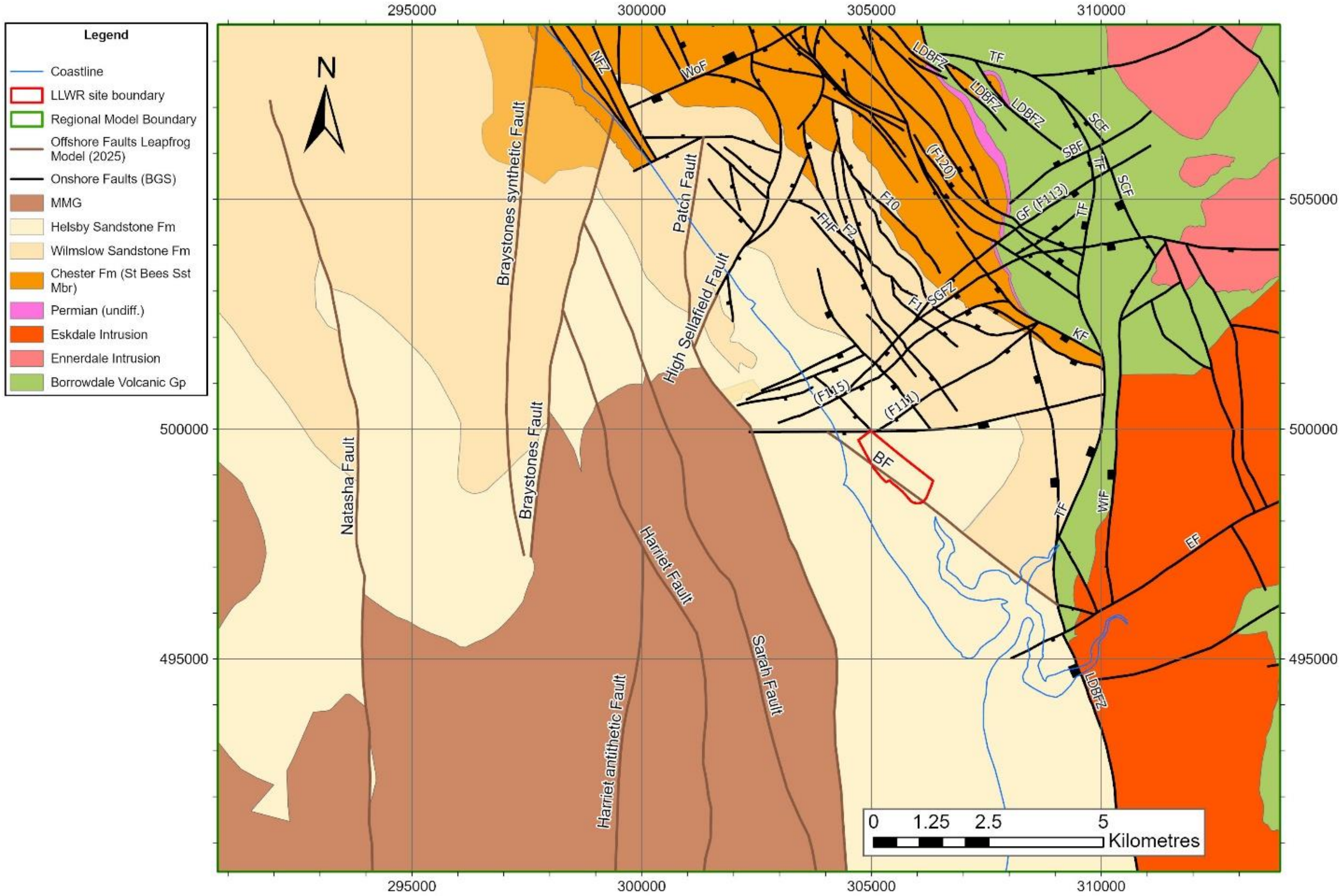


Figure 3.1: Bedrock Geological Map for West Cumbria and the adjacent offshore. Map combines various data sources: onshore geology and faults simplified from BGS bedrock geology 1:50,000 scale map data; offshore geology and faults from regional bedrock Leapfrog model. Contains BGS materials copyright NERC [21].

rocks, greater than 2,500 m thick. Intruded into the BVG are granitic and granodioritic rocks of the Lake District Felsic Plutonic Suite (Eskdale intrusion and Ennerdale intrusions), part of the larger Lake District Batholith. This igneous material forms many of the cobbles and boulders present within the Quaternary succession across the site. These Lower Palaeozoic-aged rocks are largely separated from younger sedimentary rocks of the coastal plain to the west by the Lake District Boundary Fault Zone, a north-northwest-trending fault that downthrows to the west. Resting unconformably on the BVG is Carboniferous-aged limestone, which has been proven in some of the Nirex boreholes in the area around Sellafield. The limestones are overlain by Appleby and Cumbrian Coast Group rocks of Permian age. Within West Cumbria, the Appleby Group is represented by coarse, conglomeratic deposits known as Brockram. Above this is the St Bees Evaporite Formation, consisting mainly of limestone, dolomite and anhydrite, deposited in a marine environment. The St Bees Shale Formation overlies, but partly interfingers with, the St Bees Evaporite Formation and comprises red-brown mudstone, siltstone and sandstone with some evaporite beds. These units are recognised in the geological conceptual model; however, they are grouped with the St Bees Sandstone (described below) in the 3-D digital geological model as they are limited in extent, some distance from the LLWR, and there are minimal data to support their representation.

Stratigraphically above the Cumbrian Coast Group in the region of the LLWR are sandstones of the Sherwood Sandstone Group. The oldest of these is the Chester Formation (St Bees Sandstone), which occurs at depth below the LLWR site. In the area, it is typically about 500 m thick and comprises reddish brown, fine-grained sandstone. The unit is interpreted as deposits of braided river channels.

The Wilmslow Sandstone Formation lies above the Chester Formation (St Bees Sandstone) and is recorded as being around 530 m thick in one borehole at Sellafield. It has been proven in some of the deeper boreholes at the LLWR site and typically consists of quartz-rich, cross-bedded sandstones, with an appreciable percentage of well-rounded quartz grains. These are interpreted as wind-blown, aeolian dune deposits. Also present are beds of more argillaceous sandstone, thought to represent deposition in shallow waterlain and damp aeolian conditions.

The youngest formation within the Sherwood Sandstone Group is the Helsby Sandstone, which forms the bedrock unit below the Quaternary deposits at the LLWR site. The full thickness of this unit is not present onshore, however, up to 146 m thick was proven in a Sellafield borehole, compared with the full thickness of about 215 m in the nearby offshore. The Helsby Sandstone subcrop is present along a 1 km wide coastal fringe from Sellafield to Drigg, before widening eastwards inland to Holmrook. The formation consists dominantly of reddish brown, medium-grained sandstone, with some coarse well-rounded grains. Mudstone clasts and mica are generally uncommon; some lithic (BVG) and granitic clasts have been identified. The sandstone is generally cross-bedded, with some minor argillaceous sandstones, similar to those described from the Wilmslow Sandstone. The succession was interpreted as mainly aeolian dune deposits of, with some interdune sequences. The igneous and BVG clasts are likely to have been transported by wadi-like river systems, draining the Lower Palaeozoic terrain to the east.

The youngest bedrock unit found in the area is the Triassic-aged Mercia Mudstone, which is not present onshore in West Cumbria but occurs offshore in the Irish Sea. It mainly comprises halite and red mudstone deposits.

Structurally, the bedrock in the area is cut by numerous faults. The main faults trend north-northwest to north-west and generally comprise sets of normal faults. Another important set of faults trend east-northeast to north-east, many of which appear to have a component of strike slip associated with them. Several of these have linkages to deeper Lower Palaeozoic lineaments present further east, which may have reactivated at various times

The bedrock surface has a variable weathering profile, which is typically less than 5 m thick but can be up to 11 m thick. In some places, the sandstone is completely weathered to an unconsolidated sand. The top of bedrock has been taken as the top of the weathered bedrock as, in many boreholes on the LLWR site, it is more challenging to consistently identify unweathered bedrock.

The bedrock surface also has a complex morphology because of the structural control, i.e. faults as shown in Figure 3.1 and erosion. This includes channel structures, which influence the distribution of the younger Quaternary deposits.

3.1.3 Quaternary

At the time of the 2011 ESC, the Quaternary deposits were understood to consist mainly of interbedded deposits of clayey diamicton (till or boulder clay), sandy diamicton, glacio-fluvial sands and gravels and glacio-lacustrine silts and clays. However, recent investigations and interpretations, using revised scientific methods and understanding, have produced an updated geological understanding of the Quaternary deposits in the region.

The geological conceptual model of the Quaternary deposits is made up of many units, as described in Table 3.1. For some units, the word 'Upper' or 'Lower' is used to denote the unit’s position in the stratigraphical sequence. A summary of the geological understanding of how these units formed is provided below, with the units’ codes as given in Table 3.1 in bold.

Throughout the Quaternary, the west Cumbrian coastline would have been repeatedly overridden by large-scale glaciers. Each successive event would have eroded much if not all of the deposits laid down by previous events, effectively scouring the landscape down to bedrock. As a result of this waxing and waning of ice sheets, bedrock was deeply incised and the characteristic U-shaped valleys of the Lake District were formed. The deepest and oldest Quaternary deposits (pre-Last Glacial Maximum (PrLGM)) are typified by outwash and till deposits (PrLGM-O and PrLGM-TO), and remain preserved in onshore and offshore bedrock lows.

Warming associated with the transition to an interglacial climate would have caused rapid melting and retreat of continental scale ice-masses. As a result of this, global sea levels rose rapidly and fluvial systems that had remained largely dormant or characterised by meltwater routing would have been reactivated. In the vicinity of the LLWR site, local river systems such as the Irt, Mite and Esk, which presently converge at Ravenglass, and the river Calder and Ehen to the north, near Sellafield, would have been partially inundated by this relative sea-level rise. Flooding of the lower reaches of these systems would have created estuarine conditions which are represented by the deposition of fine-grained organic muds (PrLGM-CM1). Within the LLWR site, coarser gravel beds (PrLGM-EGB) suggest the occurrence of an anastomosing or braided river system with semi-permanent or ephemeral gravel bars. As the relative sea level continued to rise, the palaeo-estuaries of the Irt, Mite, Esk, Calder and Ehen gradually became marine inlets. As sea levels rose further, this marine influence extended further inland, depositing homogenous sand units (PrLGM-MS) and marking the limits of this marine incursion. Additional fine-grained organic muds (PrLGM-CM2) suggest a relative sea-level fall followed, leading to a return to estuarine and alluvial conditions in the rivers Irt, Mite, Esk, Calder and Ehen. The alluvial sand deposits identified on the LLWR site (PrLGM-AS) likely formed once riverine processes were able to reoccupy previously flooded river valleys, following the fall in sea levels.

The retreat of ice following the maximum extent of the Devensian ice sheet in the Last Glacial Maximum (LGM) left large volumes of outwash and till (LGM-O and LGM-TO) across the west Cumbrian lowlands. This outwash deposit or ‘sandur’ exhibits evidence of meltwater channels which criss-cross the landscape. As local ice retreated from the coastal margins, the individual ice lobes likely separated (‘unzipped’) and began to retreat into their respective valleys. Wasdale and Eskdale separated and meltwater from these began to build up between the two lateral ice margins as a proglacial lake (LGM-IL) inland of the site as well as infilling meltwater channels within the sandur (PoLGM-IC) beneath the present LLWR site.

Following the collapse of global ice volumes after this maxima, Post Late Glacial Maximum (PoLGM), relative sea levels would have risen relatively rapidly. Along the west Cumbrian coastline an extensive sand unit (PoLGM-S) can be identified, which appears to extend partially inland, in part following the flooded river valleys of the Irt, Mite, Esk, Calder and Ehen. This sand is interpreted to be predominantly the result of increasingly distal, and therefore finer-grained, outwash deposition from retreating Lake District ice, and in the present-day offshore region, potentially influenced by marine sand deposition following withdrawal of LGM ice.

Following this, there was at least one readvance event, referred to as the Scottish Readvance (SR). Ice from the Lake District would have coalesced in the coastal lowlands before reaching a maximum extent. The ice from the Lake District would have been relatively small westerly facing glaciers which would likely have responded more rapidly to any climate forcing than any large ice volume coalescing in the Irish Sea Basin (Pre-Scottish Readvance (PrSR)). The initial evidence of this is the development of a sandur/outwash deposit (PrSR-O) in lee of ice advances. At the same time, large volumes of ice would have been flowing down across south-west Scotland and the Scottish lowlands. This ice mass would have flowed southwards along the Irish Sea Basin and would have travelled along the coastal margins, likely overrunning parts of the onshore region such as at St Bees, but mainly remaining in the offshore zone. Similar to during the LGM, till and outwash deposits were formed by the readvancing ice and its subsequent retreat (SR-TO). The events of the Scottish Readvance can be supported by the preserved geomorphology in the present-day land surface.

A series of geomorphological features in the vicinity of the LLWR suggest an absence of ice across the LLWR during the Scottish Readvance. Moraine features inland of the site are thought to mark the maximum extent of local valley ice originating in the Lake District (Wasdale and Eskdale), while evidence near Seascale and from the Seascale cliffs suggest a confluence and terminus for several local ice margins. This led to an area of ice-free conditions stretching between Seascale and Annaside. In this area it seems probable that a glacial ice-dammed lake (IDL) formed, fed from meltwater discharging from the local Lake District glaciers and impounded by the Irish Sea Ice Sheet (ISIS) positioned slightly to the west of the coastline. The lake sediments show a regular banding of sand and clay layers forming multiple couplets. Retreat of the ice sheet from the west Cumbrian coastline near to Annaside and Bootle would have led to a final and likely catastrophic drainage of the ice-dammed lake. During the catastrophic drainage of the lake, meltwater channels are likely to have been eroded into the surface of the former lake. Once completed and the lake all but drained, it is probable that these channels would have been repurposed by meltwater emanating from the front of Wasdale and Eskdale, thus further enhancing the depth of these structures within the lacustrine sediments and filling them with granular deposits (IDL-CI).

Widescale retreat of the ice sheet and locally sourced glaciers led to the deposition of an extensive landform assemblage across the west Cumbrian coastline. Deposits of glacial outwash, hummocky topography (SR-G), and small inland lakes (SR-IL) can be attributed to the rapid withdraw of ice and the probable down-wasting of ice in situ.

Following the final demise of ice sheets across northern Britain and other areas across major continental areas (Post-Scottish Readvance (PoSR)), global sea levels rose rapidly. Sea levels probably reached an early high stand just prior to the onset of the Windermere Interstadial but fell shortly thereafter as isostatic rebound began to outpace eustatic rise. Glaciomarine sands (PoSR-GM) are recognised offshore.

Deposition onshore during the late glacial and present interglacial (Holocene (H)) is typified by alluvial sedimentation and peat formation. The rivers Calder, Bleng, Irt and Esk along with numerous smaller tributaries would become the primary mechanism of deposition and erosion and would have meandered across the coastal lowland depositing fine grained sediments. Thicker sequences of alluvium (H-A1) occur near to the LLWR site/Drigg Beach cliffs and are thought to be the result of channel infill and subsidence related to the collapse of the underlying ice-dammed lake sediments.

Peat (H-P) would have developed in topographic lows as well as across many of the former inland lakes as these gradually infilled with sediments and became land during the Holocene. A second more extensive alluvial layer (H-A2) can be recognised overlying many of the peat and lower alluvial deposits suggesting that regional river activity may have been increased later in the Holocene. A dune system (H-D) formed along the shoreline and likely occurred at a similar time as Holocene sea levels rose. Deposition offshore is typified by beach sands along the coast (H-BS) and marine silts and muds (H-MSS) offshore.

Table 3.1: Quaternary units within the geological conceptual model

Stratigraphic unit	Distribution and relation to geomorphology
Pre-LGM Outwash (**Pr-LGM-O**)	Sands and gravels. Identifiable only in bedrock lows across the offshore and onshore environment.
Pre-LGM Till and Outwash (**Pr-LGM-TO**)	Sandy diamictons with gravels and occasional cobbles. Distributed within bedrock lows at depth below the area currently occupied by the River Irt and between the Wasdale and Eskdale valleys.
Pre-LGM Coastal Muds 1 (**Pr-LGM-CM1**)	Clays, silts and fine silty sands. Distributed within bedrock lows at depth below the area within and near to the course of the present-day River Irt.
Pre-LGM Estuarine Gravel Bed **(Pr-LGM-EGB**)	Gravels and sands. Restricted deposit identifiable within the southerly margins of the LLWR site and towards the present-day position of the River Irt Estuary.
Pre-LGM Marine Sands (**Pr-LGM-MS**)	Preserved within remnant topographic lows in the offshore environment and reaching inland.
Pre-LGM Coastal Muds 2 (**Pr-LGM-CM2**)	Clays, silts and fine silty sands. Identified within the westerly and southerly margins of the LLWR site.
Pre-LGM Alluvial Sands and Silts (**Pr-LGM-AS**)	Constrained to channel type structure. Situated within the LLWR site and extending down toward the coastline as a spatially restricted deposit. It is likely equivalents are present elsewhere; however, this is not possible to confirm with current data.
LGM Till and Outwash (**LGM-TO**)	Variable unit dominated by homogenous till units and variable gravel and sand units. Mantled across much of the higher ground inland of the LLWR and Sellafield sites.

Stratigraphic unit	Distribution and relation to geomorphology
LGM Outwash (**LGM-O**)	Variable coarse granular unit. Identified across much of the region.
LGM Inland Lake (**LGM-IL**)	Cohesive silts, sands and clays. To the east of the LLWR site and positioned between the margins of the Wasdale and Eskdale valleys.
Post-LGM Infilled Channels (**PoLGM-IC**)	Predominately cohesive silts and clays in a large channel feature. Identified beneath the LLWR site and cuts into the upper surface of LGM outwash deposits. It is likely equivalents are present elsewhere however this is not possible to confirm with current data.
Post-LGM Sands (**PoLGM-S**)	Located in deeper offshore areas and limited extent onshore relative to the current coastline in the vicinity of the LLWR site.
Pre-Scottish Readvance Outwash (**PrS-O**)	Variable granular unit. Limited extent in coastal region onshore relative to the current coastline, around the LLWR and Sellafield sites.
Scottish Readvance Till and Outwash (**SR-TO**)	Variable unit dominated by stiff, overconsolidated diamicton and sands and gravels. Extensively distributed across coastal lowland and partially extending back into valleys.
Ice Dammed Lake (**IDL**)	Alternations of predominantly sand and clay units. Laterally extensive across LLWR site and thicker in topographic lows, limited extent regionally to close to LLWR site.
Scottish Readvance Glaciofluvial units (**SR-G**)	Variable granular unit. Distributed in local valleys aligned with ice emanating out of the Lake District. Extensive deposits on the coastal lowlands to the north of the LLWR.
Scottish Readvance Inland Lake (**SR-IL**)	Variable unit with highly variable thicknesses. Occurring in retreat areas of local ice margins predominantly inland of the LLWR.

Stratigraphic unit	Distribution and relation to geomorphology
Ice Dammed Lake [Channel] (**IDL-CI**)	Variable channel infill granular deposits, only found at LLWR. Channel infill cutting into alternating sands and clays of the ice-dammed lake deposits.
Post-Scottish Readvance Glaciomarine sands, clays, and silts (**PoSR-GM**)	Typically a diamicton of sandy, silty clay. Only found offshore.
Lower Alluvium (**H-A1**)	Highly variable. Typical examples include a fine-coarse gravelly sand to a clayey silt/silty clay. Associated with topographic depressions in the underlying lake surface.
Peat/Organic Clay (**H-P**)	Associated with alluvial deposits, typically infilling small topographic depressions.
Dune (**H-D**)	Dune field occupying some of the shoreline and extending across Ravenglass spit.
Upper Alluvium (**H-A2**)	Highly variable. Extensively identified across the wider region.
Holocene Marine/ Beach Sands (**H-BS**)	Granular unit. Predominantly along present coastline as indicated by modern beaches.
Made Ground (**MG**)	Thin, typically less than 1 m of man-made deposits. Highly variable.
Holocene Marine Silts and Muds (**H-MSS**)	Only found offshore. Most recent marine deposition.

Figure 3.2 presents a conceptualisation of sea-level changes in West Cumbria and the relationship of these with the regional climatic strato-type and stratigraphic framework. Figure 3.3 presents a schematic section through the LLWR site perpendicular to the coast to show the relationships and typical properties of the stratigraphy. It is not reflective of a single location.

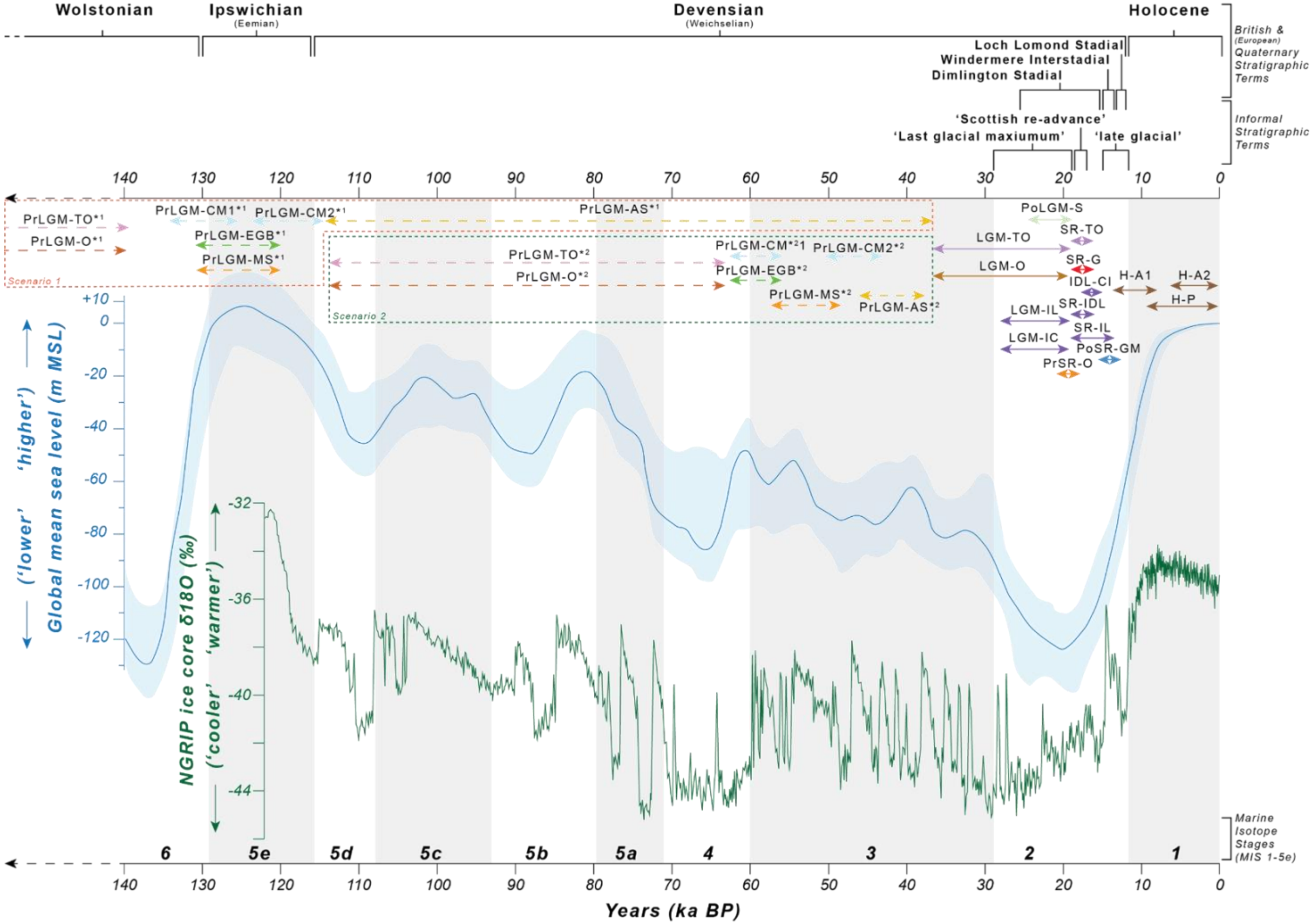
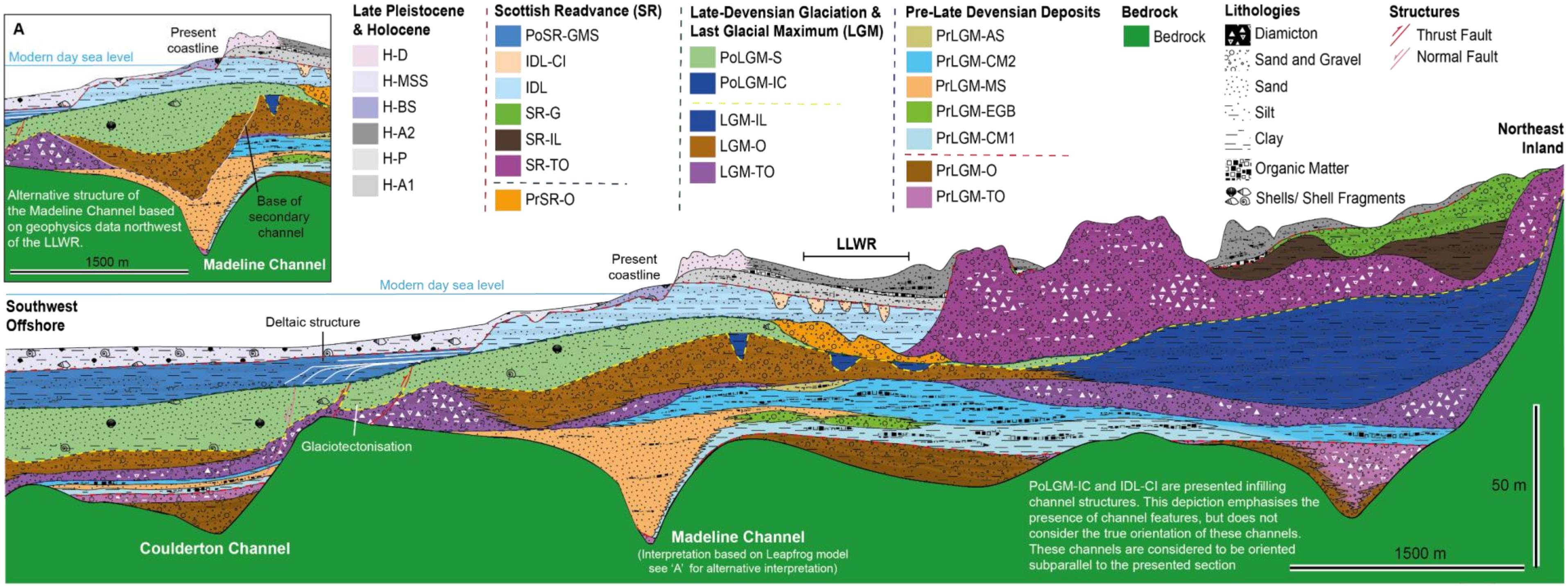


Figure 3.2: Conceptualisation of sea-level changes in west Cumbria and the relationship of these with the regional climatic strato-type and proposed stratigraphic framework. A dashed line denotes a period of chronological uncertainty [21].



H-D - Holocene Dunes; **H-MSS** - Holocene Marine Silts and Sands; **H-BS** - Holocene Beach Sands; **H-A2** - Holocene Upper Alluvium; **H-P** - Holocene Peat and Organic Clays; **H-A1** - Holocene Lower Alluvium; **PoSR-GMS** - Post Scottish Readvance Glaciomarine Sands; **IDL-CI** - Ice Dammed Lake Channel Infill; **IDL** - Ice Dammed Lake; **SR-G** - Scottish Readvance Glaciofluvial; **SR-IL** - Scottish Readvance Inland Lake; **SR-TO** - Scottish Readvance Till and Outwash; **PrSR-O** - Pre Scottish Readvance Outwash; **PoLGM-S** - Post Last Glacial Maximum Sands; **PoLGM-IC** - Post Last Glacial Maximum Infill Channels; **LGM-IL** - Last Glacial Maximum Inland Lake; **LGM-O** - Last Glacial Maximum Outwash; **LGM-TO** - Last Glacial Maximum Till and Outwash; **PrLGM-AS** - Pre Last Glacial Maximum Alluvial Sands; **PrLGM-CM2** - Pre Last Glacial Maximum Coastal Muds 2; **PrLGM-MS** - Pre Last Glacial Maximum Marine Sands; **PrLGM-EGB** - Pre Last Glacial Maximum Estuarine Gravel Beds; **PrLGM-CM1** - Pre Last Glacial Maximum Coastal Muds 1; **PrLGM-O** - Pre Last Glacial Maximum Outwash; **PrLGM-TO** - Pre Last Glacial Maximum Till and Outwash.

Figure 3.3: Schematic section through the LLWR site perpendicular to the coast to show the relationships and typical properties of the stratigraphy. It does not correspond to a single location [21].

3.2 3-D Geological Model Development

The purpose of the geological model is to provide a basis for the hydrogeological model that is used to model contaminant pathways in the subsurface. For the 2011 ESC, a new lithofacies approach was adopted to allow the development of a 3-D geological model [48]. This enabled the translation of complex geological data into a format suitable for hydrogeological modelling by grouping geological units based on their physical and hydraulic properties, rather than solely on depositional history or stratigraphy. Nevertheless, the interpretation took into account the understanding of the geological history and the BGS stratigraphy, but these considerations were secondary to the overall composition and hydrogeological characteristics of the Quaternary deposits. Additional interpretation of the glacial event sequence and depositional environments of the Quaternary deposits and modelling since the 2011 ESC have demonstrated that many of the units previously regarded as tills are actually glacial lake deposits; however, the lithofacies units presented in the 2011 ESC largely remain unchanged in the current geological conceptual model, as they are based on compositional and textural characteristics, rather than depositional environments.

The progress made since 2011 with the geological understanding and development of a regional- and site-scale conceptualisation, has allowed the update of the conceptual model using a detailed event-based stratigraphy. This has led to a revised 3-D digital geological model (utilising Leapfrog Works™) to represent the new geological knowledge. Use of Leapfrog Works allowed early visualisation of the interpreted data and avoided the need to reconcile many 2-D geological sections. This meant very early geological models were primarily data-driven, and geological interpretation away from observational data (conceptualisation) could be applied after iterative interpretation of the observational data with the benefit of 3-D visualisation.

Through a process of iteration, four models have been developed: bedrock surface (Quaternary-bedrock boundary), bedrock stratigraphic model, Quaternary site-scale model and the Quaternary regional-scale model, as shown in Figure 3.4. Regional- and site-scale 3-D digital geological models include an improved understanding of the bedrock compared with previous models and a detailed representation of Quaternary channel features identified on the site. The new geological understanding allowed us to reduce uncertainty in extents and positions of various key geological units. A summary of the model development is provided here (see Figure 3.5), however, details of the specific data applied to the models, modelling decisions and rationale, and the resulting 3-D digital geological models are presented in an accompanying report [22].

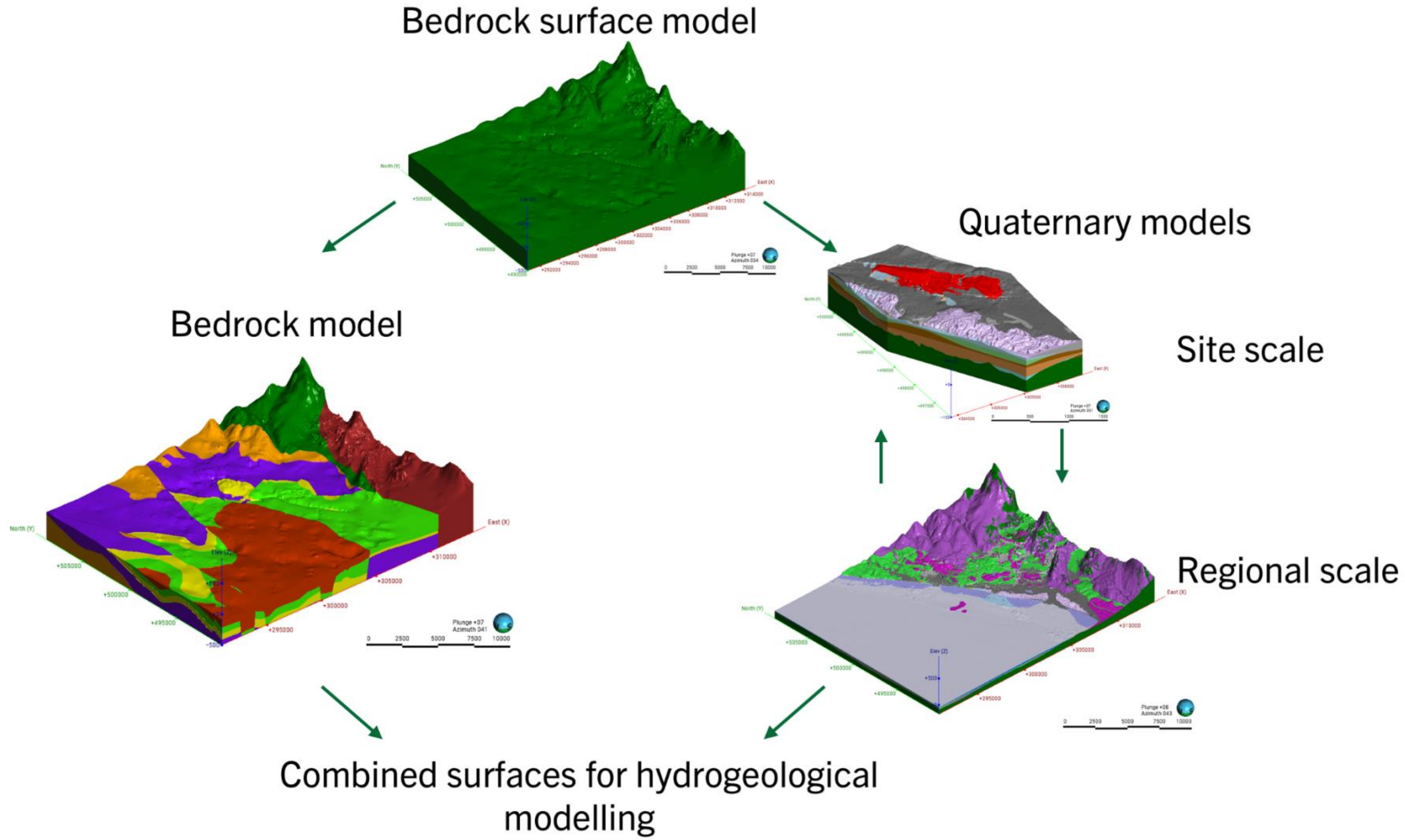


Figure 3.4: Relationships of the four separate models to one another and their integration [21]

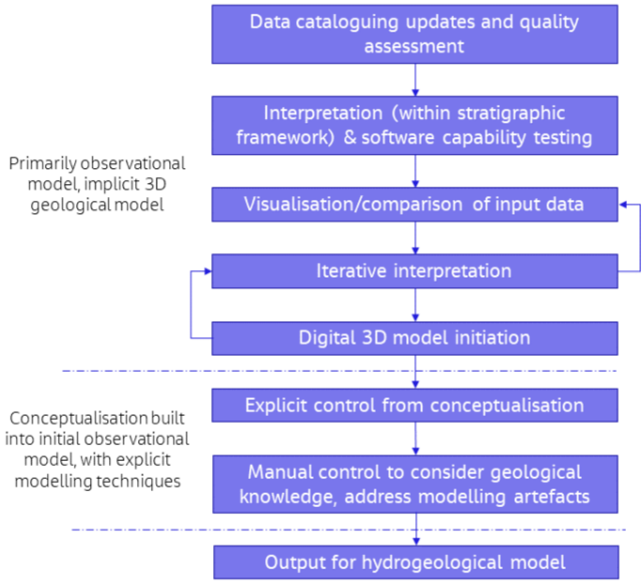


Figure 3.5: Overview of 3-D digital model build process applied for the geological model.

3.2.1 Model Extent

For hydrogeological modelling, there is a higher resolution site-scale model and a lower resolution regional model to expand the model to suitable boundary conditions. At a minimum, the geological model needed to cover the extent of the regional hydrogeological model. However, some of the boundary conditions for the hydrogeological regional model are informed by the geological model, meaning that it is of value to continue the geological model beyond that boundary to allow assessment of the suitability of those boundary conditions. The geological model extent is also driven by data availability. Significantly more data on the bedrock structure are available offshore compared with onshore due to offshore geophysics data collection. It is of value to include a reasonable distance offshore to capture these data in the geological model to represent the offshore bedrock structure, and therefore illustrate the typical structural regime and reduce uncertainty in the boundary conditions. Figure 3.6 shows the resultant regional geological model extent, to enclose the hydrogeological model and a reasonable volume of offshore geophysics data.

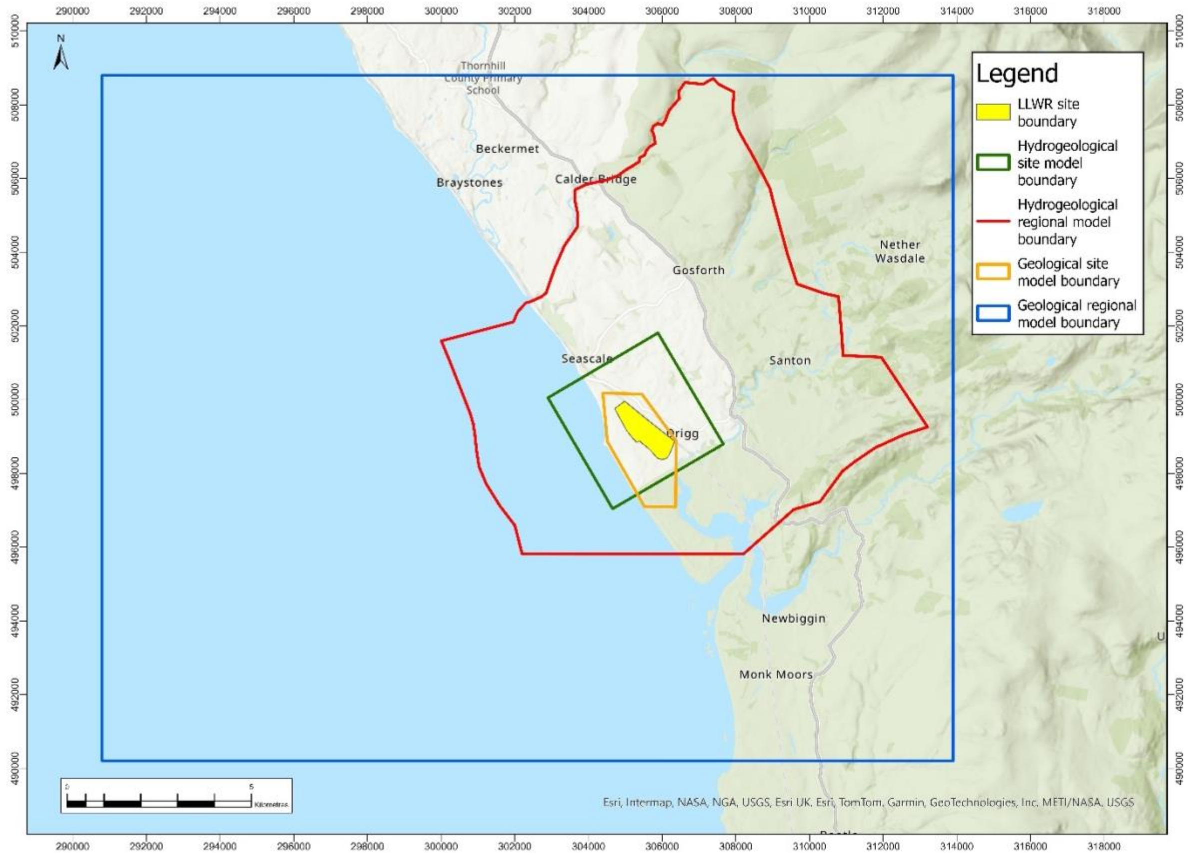


Figure 3.6: **Extent of geological and hydrogeological regional- and site-scale models [21]**

3.2.2 Model Inputs

Given the history of the LLWR site and substantial modelling efforts for previous ESCs, there is a large volume of input data available for a geological model, of variable age, quality, format, distribution, and prior interpretation.

Available input data were collated and catalogued. All input data used for the models have been re-interpreted or re-evaluated for this geological model in the context of the conceptualisation developed for the model build. They have also been integrated with the additional data collected since the 2011 ESC model build.

Although all data were reviewed, not all the available data were included in the model build. Inclusion of data in the model was limited by both the scope of work (regional extents) and a quality assessment. Further details of the model build and data evaluation and selection are provided in the geological model report [22]. More details on the interpretation of the intrusive data within the model is included within the conceptual geology report [21].

The data used directly within Leapfrog Works to produce the 3-D digital geological model are as follows.

- A total of 1,249 records of intrusive investigations. These include boreholes, CPTs, excavations and trenches. Of these, 641 were only used for the bedrock surface elevation. Of the remaining 608, the majority include information on the Quaternary sequence, while a minority provide data on only core bedrock. Figure 3.7 and Figure 3.8 show the intrusive data included in the geological model at the regional and site scale respectively. HOLEBASE™ is used as the LLWR's authoritative database for recording and managing geological and environmental monitoring installations. The majority of LLWR boreholes are shallow to moderate depth, terminating within the Quaternary sequence, with depths typically sufficient to characterise superficial deposits. A limited number of deep boreholes penetrate through the full Quaternary succession and into sandstone bedrock, with the deepest boreholes reaching approximately 100 m below ground level.

- Table 3.2 describes the intrusive data and how they were used in the model.
- Data from 18 additional boreholes drilled on the LLWR site in 2021; 10 sonic-drilled boreholes focused on the Quaternary sequence, and 8 rotary-drilled boreholes focused on the bedrock [49].
- Data from 18 Ravenglass cores that were published in 2021, adding shallow detail to the Ravenglass estuary area [50].
- Over 2,700 km of geophysics data, including 2-D reflection, refraction and resistivity datasets. The quality was highly variable between datasets, including variation in available data format (raw, processed, or only images). Table 3.3 describes the geophysics data and how they were used in the model. In some cases, full interpretations of the surveys were not included where they did not add certainty to the model. This is further discussed in the geological model report [22]. Figure 3.9 and Figure 3.10 show the available geophysics data for the region and site respectively.
- Downhole wireline geophysics from the eight rotary cored LLWR 2021 boreholes were interpreted to support the model.
- Data from six offshore legacy oil and gas wells have been used to aid offshore geophysics interpretations. Locations shown on Figure 3.9.
- The 'BGS bedrock elevation' data [51] have been included in earlier models but are of unknown original provenance, so are used with caution only in areas of data gaps.
- Geomorphological mapping, primarily from LiDAR, of the West Cumbria region. This is from a combination of previous work and recent research [52]. Figure 3.11 shows an updated geomorphological map for West Cumbria, which was used as both direct input data to the model for some units and landforms, and as an input for conceptualisation. This includes a review of historical stream positions on the LLWR site, referred to as the Streams Study [53].
- The cliff sections, at Drigg Beach [54] and Seascale [55] were logged and the observations integrated with borehole, geophysical, and geomorphological data to refine the stratigraphic framework, ensuring that it reflected both the physical

properties and the depositional history of the units. The interpretations were corroborated by micromorphological analysis and geotechnical testing.

- Topography and bathymetry data, from a combination of the Environment Agency publicly available LiDAR [56] and accessible bathymetry datasets from 1998 and 2021 [57] and the 2016 Moorside MBES [37], provided the surface boundary conditions for the geological model and to assign elevations to the tops of specific stratigraphic units, especially where borehole data were sparse.

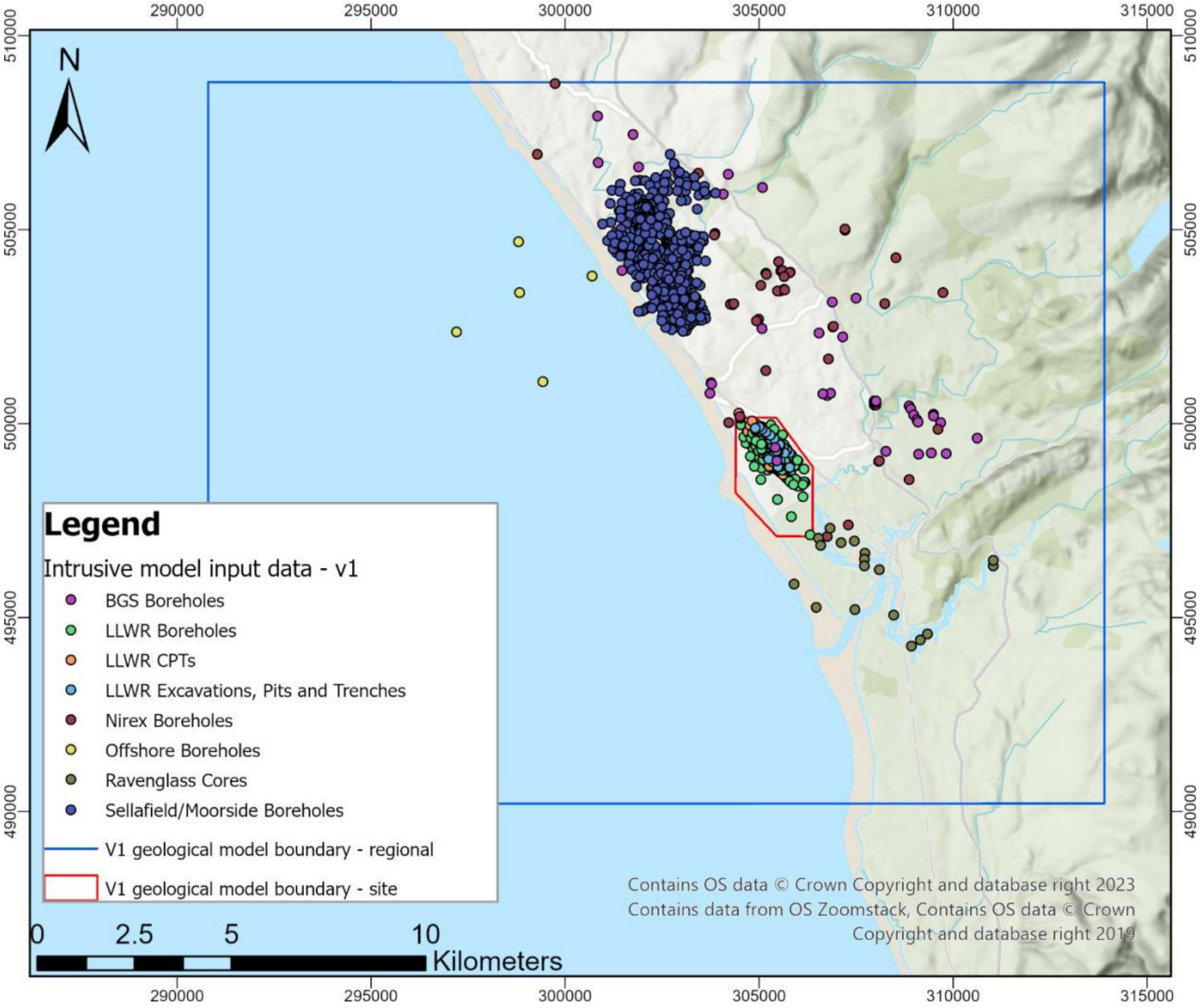


Figure 3.7: Ground investigation data utilised for the version 2 geological model across the regional scale [21]

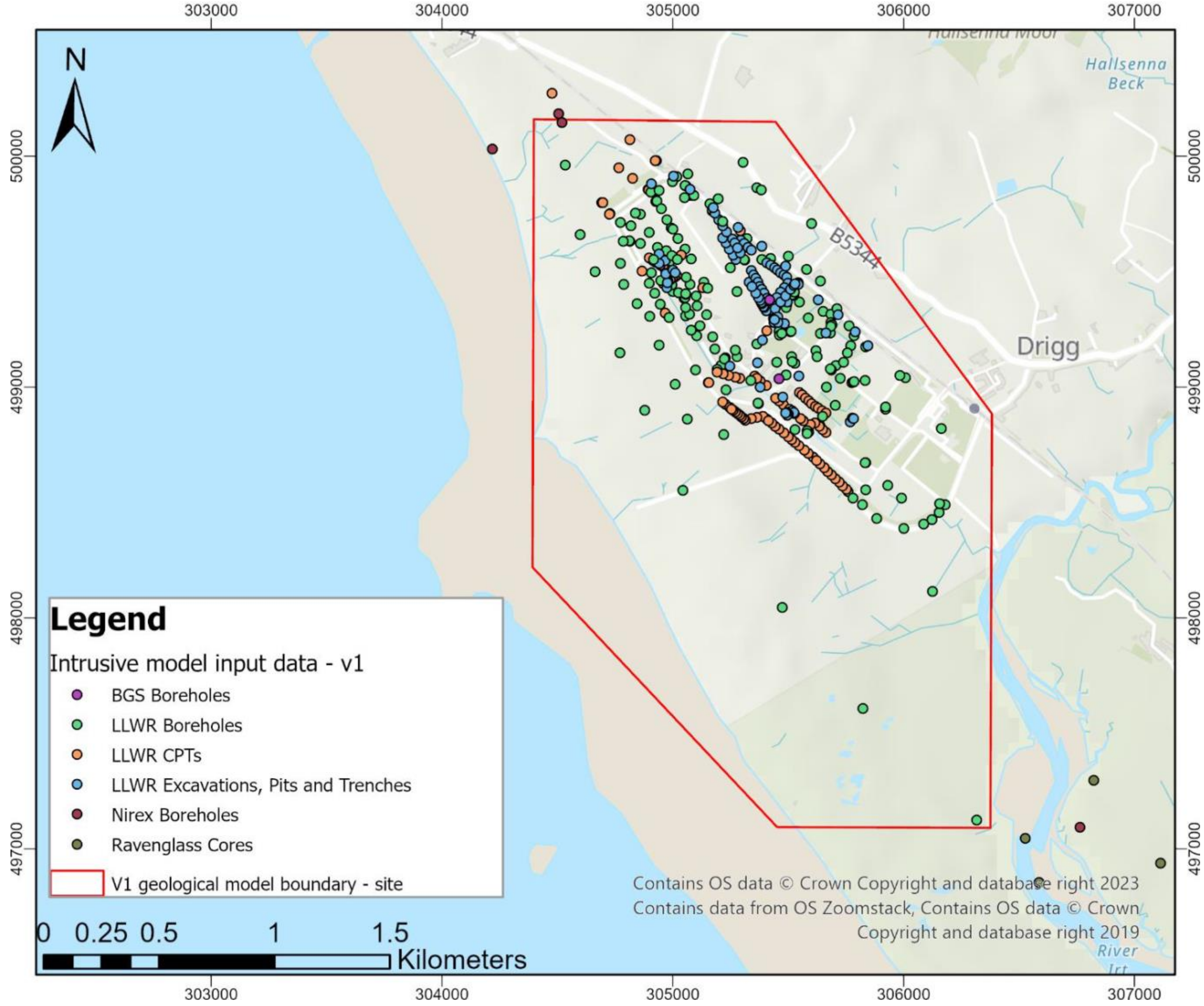


Figure 3.8: **Ground investigation data utilised for the version 2 geological model across the site scale [21]**

Table 3.2: Ground investigation data utilised for the geological model

Dataset name	Description	Total number of data points	Use in model development
LLWR Boreholes (sonic, rotary, cable percussion)	Boreholes held by LLWR either on the site or in close proximity.	208	Most information is for Quaternary sequence; only 2021 boreholes offer division of bedrock units using wireline logs.
LLWR CPTs	Cone penetration tests on the LLWR site or in close proximity.	98	CPTs only provide information for top Quaternary sequence, typically being terminated above, or interpreted to terminate on the youngest outwash unit.
Excavation logs	Excavations on the site, mostly vault construction but also for lagoons, through 2021 and 2022 logged by Jacobs' geologists.	83	Of limited use in the model; only very shallow Quaternary deposits not modelled in significant detail.
Sellafield boreholes	Boreholes available from the Sellafield site.	681	Predominantly used for bedrock elevation only but also selected high quality Quaternary holes to support regional model.
BGS Boreholes	Freely available boreholes from BGS Viewer online.	68	Support regional Quaternary model and bedrock

Dataset name	Description	Total number of data points	Use in model development
			elevation, but quality often poor.
Nirex Boreholes	Regional boreholes from the Nirex investigations.	36	Support regional Quaternary, bedrock surface and complex bedrock models, due to wireline logging within some boreholes, which allows division of the sandstone bedrock.
Ravenglass Cores	Cores collected to investigate the Ravenglass Estuary and published in reference [50].	17	Limited to Ravenglass estuary and very shallow Support regional Quaternary model.
Offshore Boreholes	Regional boreholes from Moorside Investigation, and others. There are additional boreholes offshore used where borehole geophysics is available to correlate with seismic data, these are discussed as part of geophysics input data.	5	Support regional Quaternary and bedrock models.

Table 3.3: Geophysics data used for the geological model

Dataset name	Description	Volume and distribution	Use in model
RTS reprocessed lines (HY832D1002)	Offshore 2-D seismic reflection lines. Reprocessed for this work.	Offshore, close to coastline, numerous lines.	Top Bedrock, Triassic horizons, faults.
BNFL seismic (BNFL-89 and BNFL-93)	Offshore, shallow 2-D seismic lines, raster images interpreted in Leapfrog. Mainly used for Quaternary stratigraphy and top bedrock pick. Georeferenced images with limited 1-D depth conversion.	Offshore, mainly NE-SW trending lines close to coastline.	Top Bedrock, and input to Quaternary conceptual cross-sections.
GE922D003 (Schlumberger)	Offshore regional 2-D seismic reflection lines	Offshore, covers wide area, numerous lines.	Top Bedrock, Triassic horizons, faults.
H832 series (HY832D1001)	Offshore regional 2-D seismic reflection lines.	Offshore, covers wide area, numerous lines.	Top Bedrock, Triassic horizons, faults.
TOC83 series (AR832D0022)	Offshore regional 2-D seismic reflection lines.	Offshore, covers wide area, numerous lines.	Top Bedrock, Triassic horizons, faults.
BGS-88	Onshore BGS 2-D reflection seismic lines.	Onshore, five lines in Sellafield area.	Top Bedrock, Triassic horizons, faults.
UK93-HF series & inland TerraDat high resolution seismic	Nirex 2-D seismic lines.	Onshore, east LLWR.	Fault guidance and Top Bedrock guidance.

Dataset name	Description	Volume and distribution	Use in model
	Georeferenced images.		
Moorside (Offshore: MOF; Onshore: MON)	Ultra-high resolution and high resolution 2-D seismic reflection lines, time and depth domains.	Onshore and offshore. Offshore lines close to coast, orientated NW-SE and NE-SW; six onshore lines (N-S, NE-SW, NW-SE)	Quaternary offshore, Top Bedrock, high quality.
Jacobs_LLWR_2021 seismic reflection dataset	Onshore, 2-D shallow 2-D seismic reflection dataset.	Covers area in and immediately surrounding LLWR site.	Top Bedrock, Top Wilmslow Sandstone, faults. Interpretations used to support conceptualisation and channel control in Quaternary site model.
Jacobs LLWR_UHRSR_2023 seismic reflection dataset	Ultra-high resolution 2-D seismic reflection lines, time and depth domains.	Covers area in and immediately surrounding LLWR site.	Supports control of Quaternary structures and stratigraphy onshore.
HVSR data	Horizontal to vertical spectral ratio data (passive seismic).	In and around LLWR site.	Used to define Top Bedrock surface locally around LLWR site. One survey collected in 2020 and an additional survey in 2023.
RSK_2009	Resistivity data.	On LLWR site and along the coast of Drigg Spit.	Supports channel control within Quaternary site model, particularly Irt channel, and Post

Dataset name	Description	Volume and distribution	Use in model
			LGM Sands position.
TerraDat resistivity and refraction. 1996, 2000 and 2002			Generally low quality, supports site-scale Quaternary conceptual control, but primarily the higher quality RSK equivalent is used over this dataset.

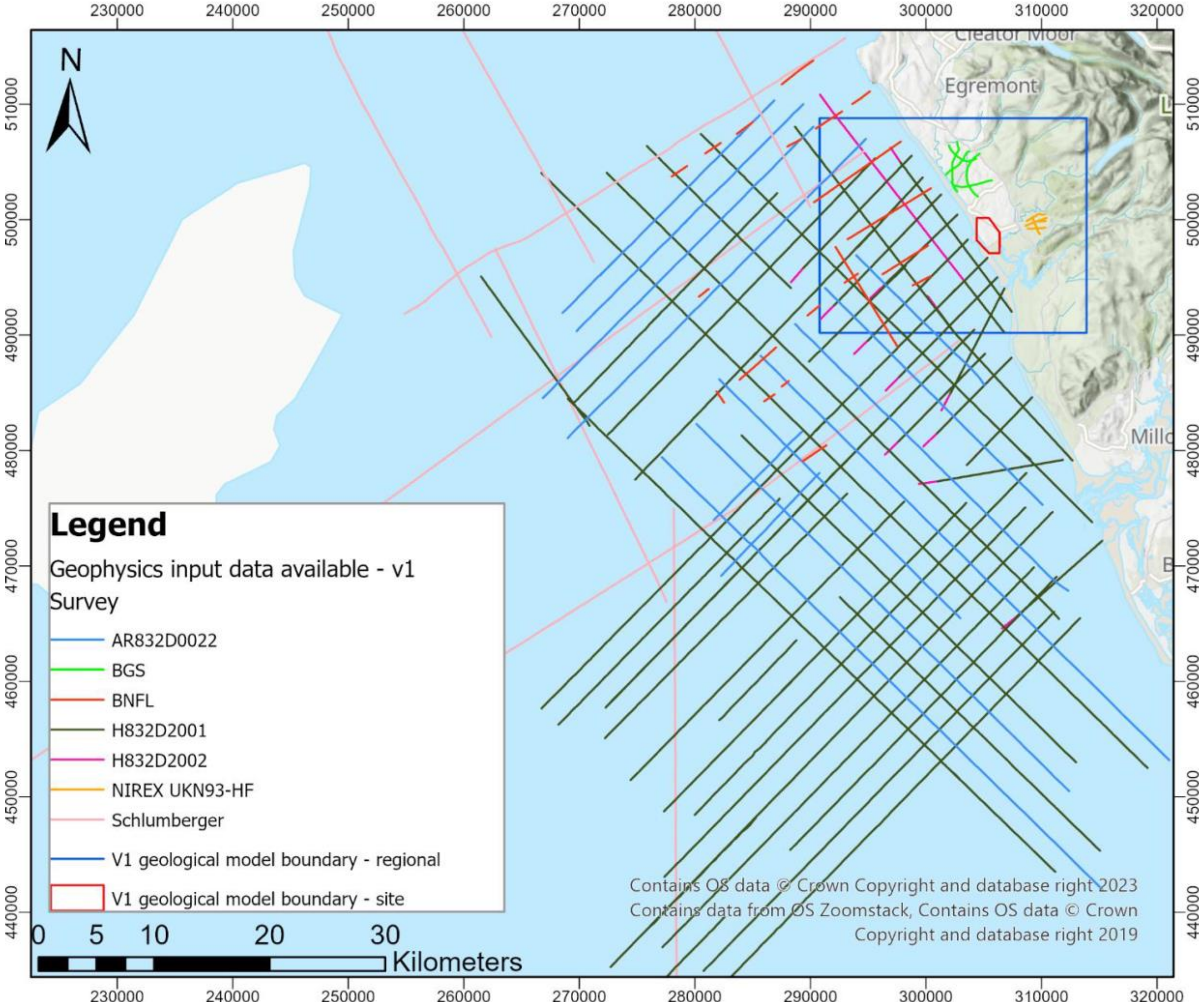


Figure 3.9: All geophysics input data available in the region for the version 1 geological model. Datasets on the site are shown separately. Not all data were utilised directly in the model [21].

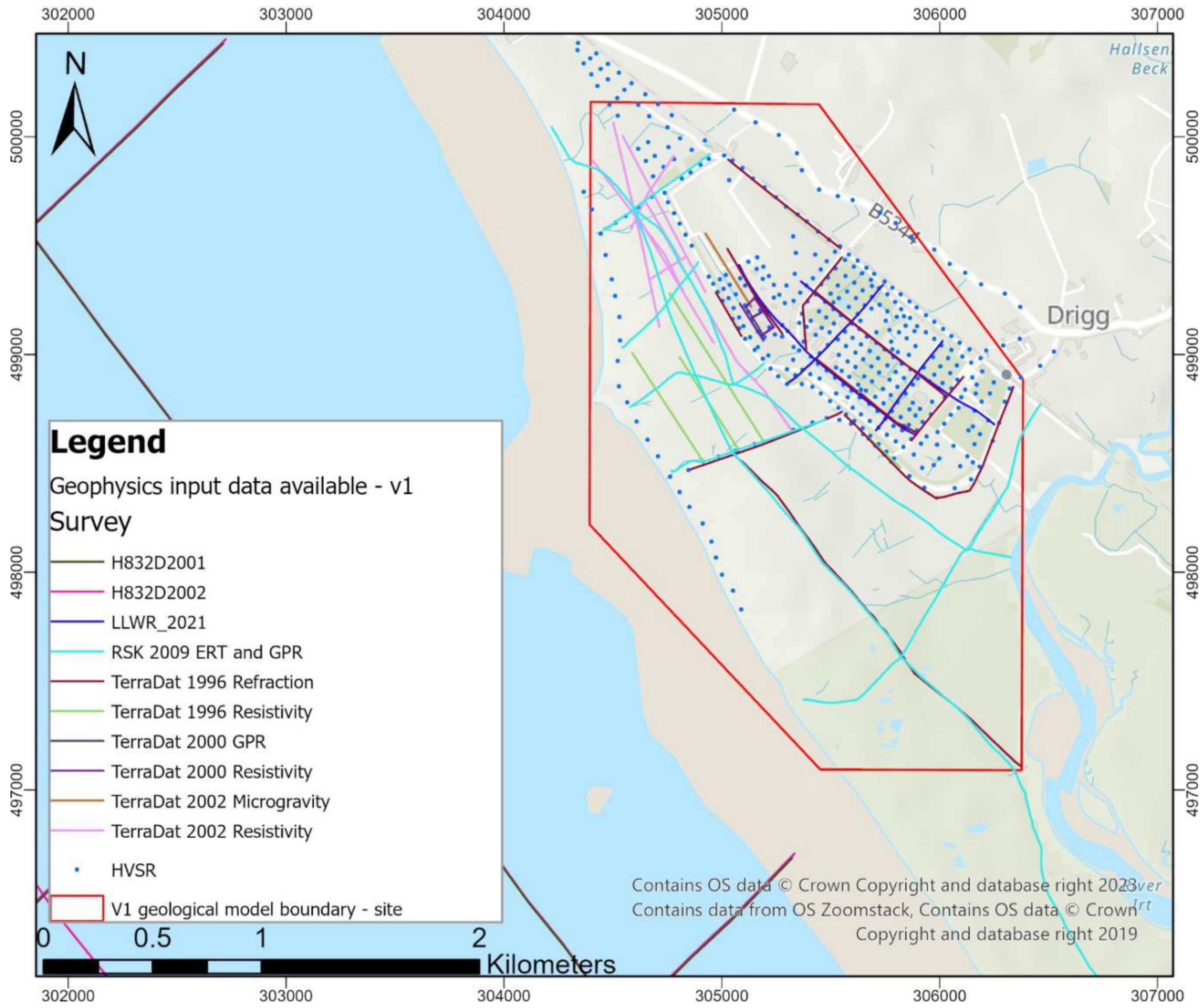


Figure 3.10: **All geophysics data available in the proximity of the LLWR site for the geological model [21]**

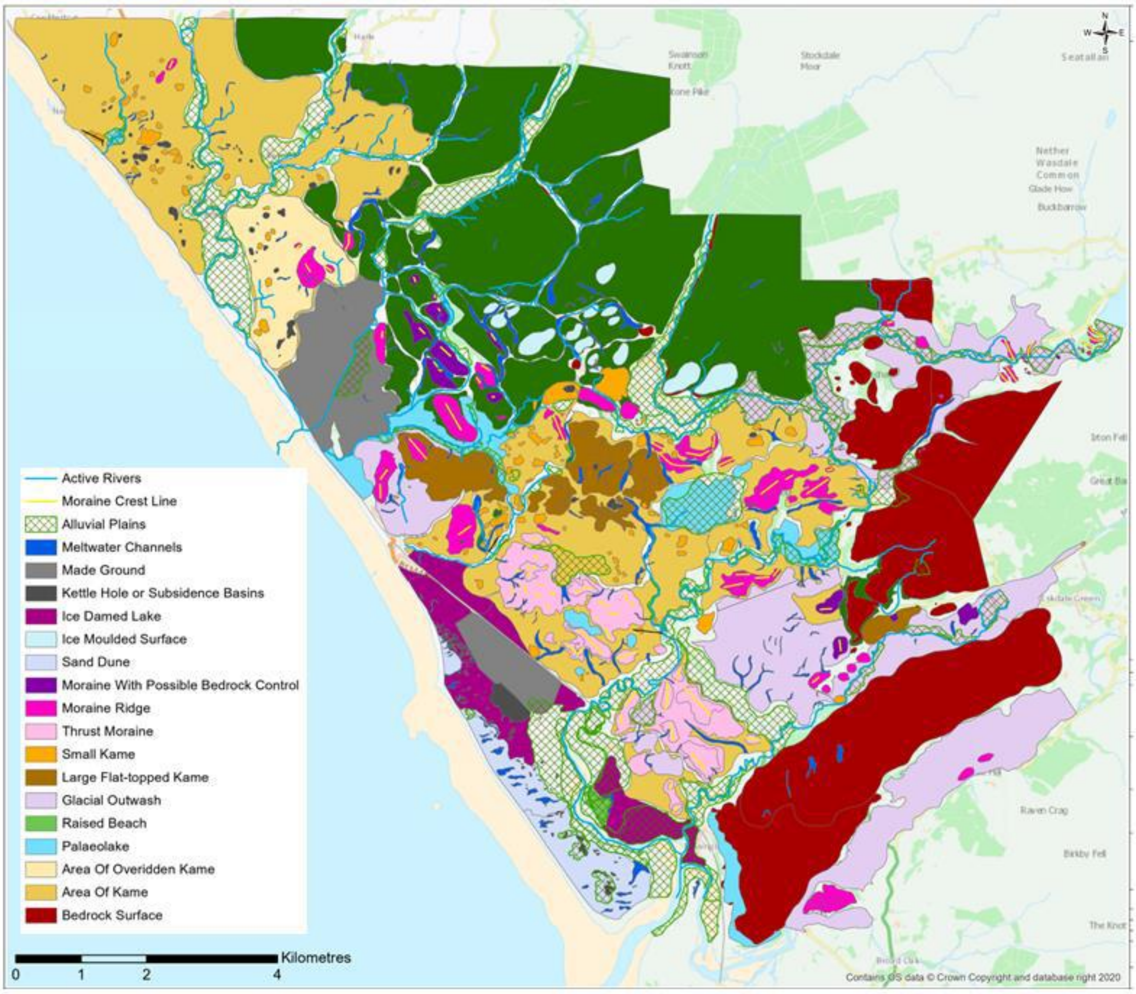


Figure 3.11: Geomorphology map as of December 2022 utilised in version 1 of geological model [21]. This is a combination of Jacobs mapping from LiDAR and input from Sinead Birks, Imperial College London PhD student [52].

3.2.3 Geological Models

3.2.3.1 Site-scale Quaternary Model

To account for the site-scale variability of the Quaternary units and the spatial resolution restrictions of the regional-scale model, a site-scale model of the Quaternary units was produced. Figure 3.12 a) depicts the site-scale model, with b) placing that into the wider regional context. Twenty-one Quaternary units are recognised. They are presented in cross-section in Figure 3.13.

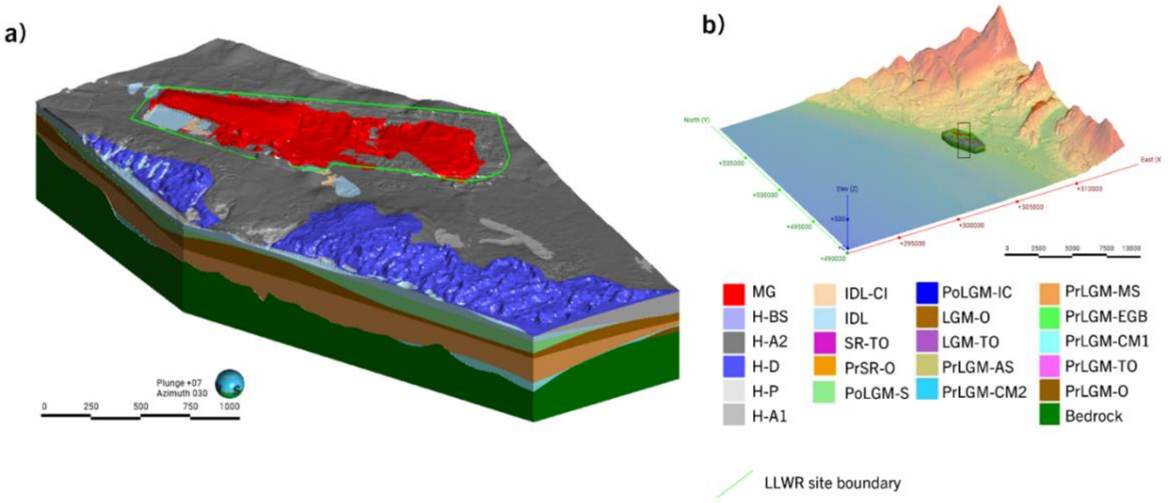


Figure 3.12: Oblique view of the Quaternary site model: a) model view. Leapfrog visualisation, Vertical exaggeration x5, b) regional location map [21]

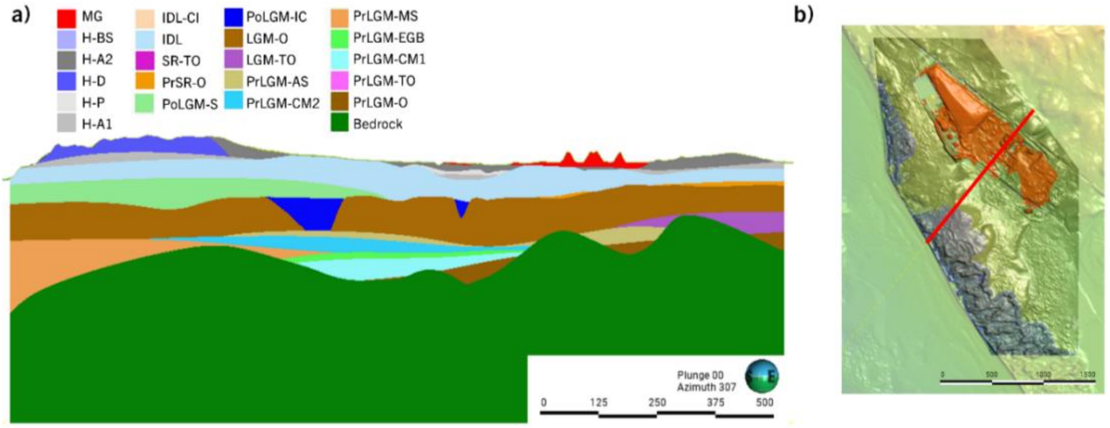


Figure 3.13: North-east trending cross-section through the Quaternary site model: a) cross-section, b) location map. Leapfrog visualisation, Vertical exaggeration x5. Scale bar in metres [21].

The deepest and oldest units are spatially restricted occurring primarily in sheltered bedrock depressions (PrLGM-O and PrLGM-TO). These in turn are overlain by deposits associated with sea-level fluctuations thought to have occurred sometime prior to the late Devensian (LGM) glaciation (PrLGM-CM1 to PrLGM-MS). Laying distinctively over these combined older units is an extensive glacigenic deposit believed to be associated with late Devensian (LGM) ice sheet movements (LGM-TO and LGM-O). This unit is cut by channel features, seen in Figure 3.13, as cross-sectional in form (PoLGM-IC), and was likely caused by ongoing glaciofluvial outwash development. A sandy unit (PoLGM-S) lies to the west and may have also be lain down as part of outwash processes or may reflect a short lived glaciomarine incursion. These LGM aged units are overlain by a glaciolacustrine unit (IDL), formed during the Scottish Readvance by the damming of glacial meltwater. Across the top of this unit and cutting down into it are channel features, likely caused following emptying of the lake and the reestablishment of glaciofluvial drainage networks (IDL-CI). Forming the upper most units in the site-scale model are deposits attributed to a series of late glacial and Holocene-aged processes, chiefly the development of alluvial systems (H-A1, HA2), peat formation (H-P) and the emplacement of a dune field (H-D) and beach sands (H-BS) associated with sea-level rises during the mid to late Holocene. At the top of the model is the made ground (MG) associated with the historical development of the LLWR site.

Previous reports on the geological understanding of the LLWR at the site scale have produced sections to demonstrate the current understanding. Reproducing the same sections as previously presented allows comparison of the evolving understanding in a single location. The following figures reproduce the sections (Sections 1, 2 and 3) that were shown in Michie et al. 2010 [31] for comparison with the Eaton et al. 1996/1997 [35, 58] stratigraphy, which supported the BNFL 2002 PCSC, the BGS lithostratigraphy [59] and the 2010 regional lithostratigraphy. The locations of Sections 1, 2 and 3 are shown in Figure 3.14.

Section 1 roughly follows the inland boundary of the site from borehole C1 to C11, as shown in Figure 3.14. A comparison of iterations of Section 1 is shown in Figure 3.15. The general structure of the Quaternary deposits is consistent through the sections.

A notable difference with previous interpretations is the layering shown in the upper 10 to 15 m. Previous models show multiple stratigraphic units in this depth range as the boreholes show alternation between clays and silts. The updated model shows only one unit, the Ice Dammed Lake unit. The updated model does not disregard the layering. Layering within the Ice Dammed Lake is interpreted and separately represented in a variant model to support hydrogeological sensitivity studies [24]. The Ice Dammed Lake variant model links layers of clay/silt dominated deposits together in ‘C’ units, and sand dominated deposits in ‘S’ units.

Another difference is the representation of channel features. Correlation of glacial deposits in the 1990s and early 2000s broadly assumed continuity of glacial deposits with some indication of features such as kettle holes to explain localised variations in permeability. In comparison, the updated geological model explicitly represents these variations in permeability as channel features.

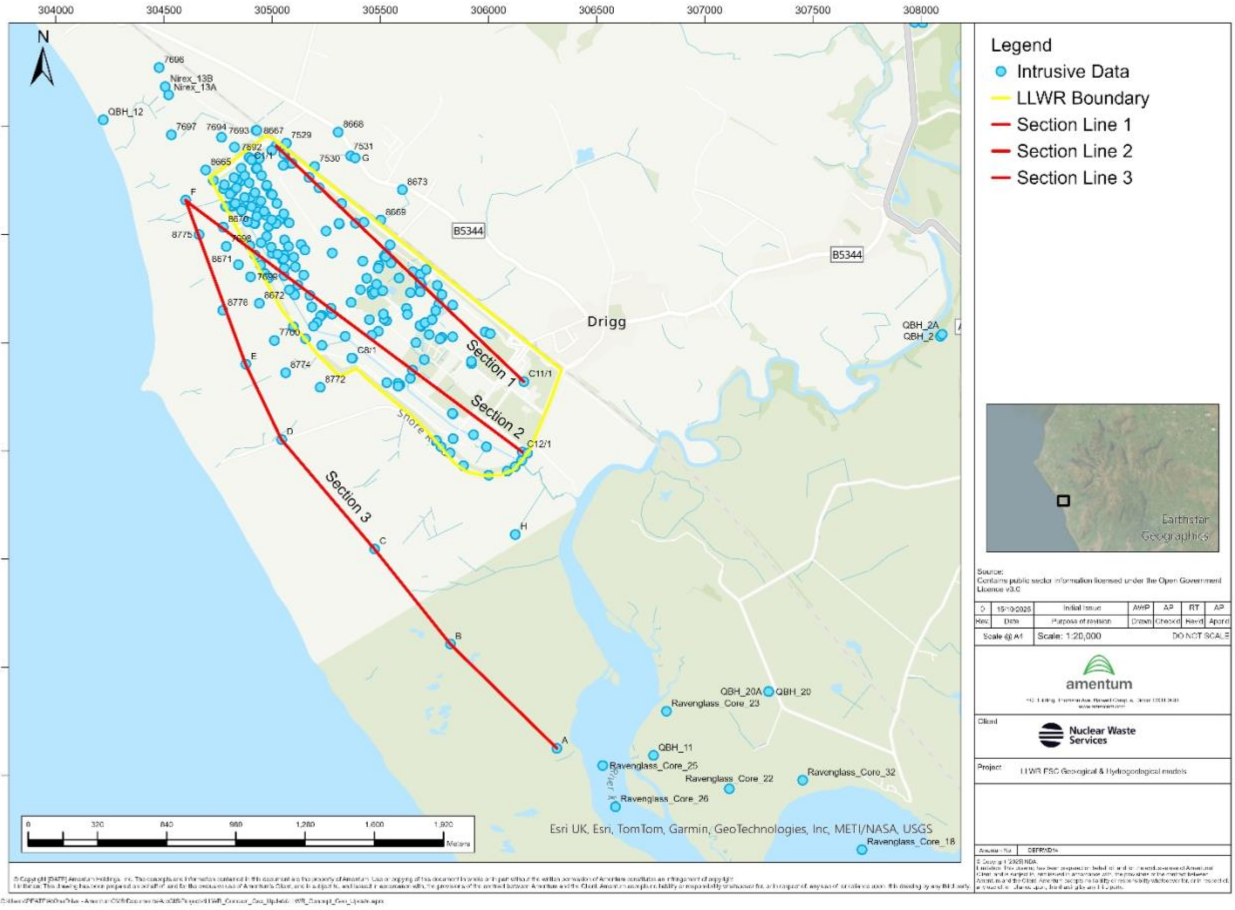


Figure 3.14: Map of LLWR showing locations of Sections 1, 2 and 3 for comparison to previous geological models [21].

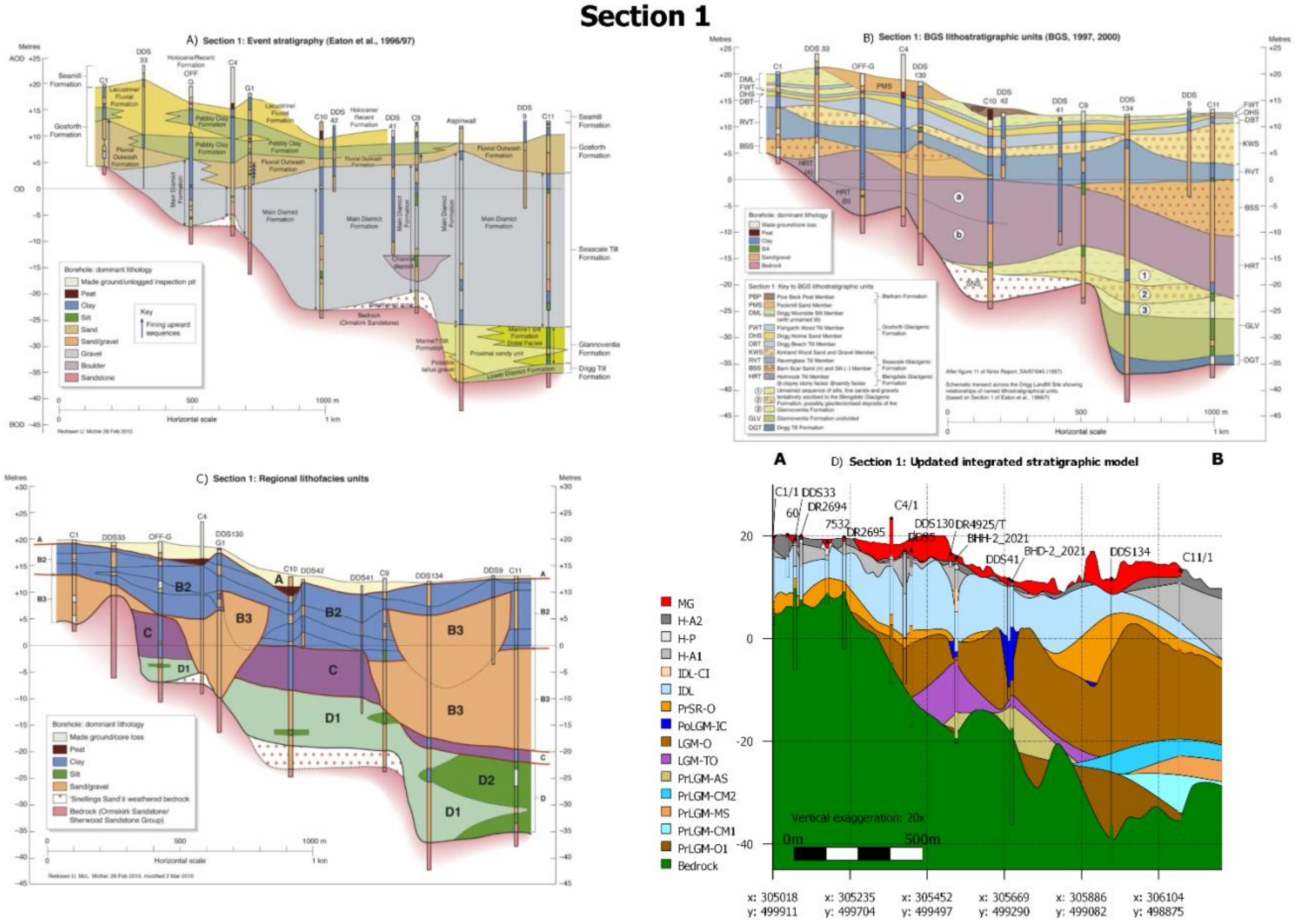


Figure 3.15: Comparison of previous interpretations: a) Section 1, Eaton et al. 1996/1997 [35, 58], b) BGS Merritt and Auton 2000 [59], c) regional lithofacies sections reproduced from Michie et al. 2010 [31], and d) the updated integrated stratigraphic model [21]. Figures placed side by side to allow comparison.

Section 2 is roughly parallel to Section 1, coastward, crossing the coastal boundary of the LLWR site. Section 2 runs from borehole F in the north-east to borehole C12 to the south-west, as shown in Figure 3.14. A comparison of iterations of Section 2 is shown in Figure 3.16.

The updated geological model introduces more detail compared with the 1990s approach, which grouped sands, gravels, and clays into the Main Diamict Formation with limited recognition of channels. The new lithofacies method separates units based on lithology and depositional processes, improving predictions of spatial variation. Sands and gravels are now divided into Post-LGM sands, Post-LGM infilled channels, and Pre-Scottish Readvance outwash, supported by geophysics and borehole data. The Ice Dammed Lake unit retains its layered sands and clays but includes channel infill features for thicker sand and gravel lenses. Near the surface, Holocene deposits are split to show made ground and peat within the alluvial sequence. At depth, the previous two layers (Lower Diamict and Marine Silt) are replaced by Pre-LGM outwash, coastal muds, estuarine gravel beds, and marine sands, allowing better modelling of low-permeability layers and their depositional environments.

Section 2

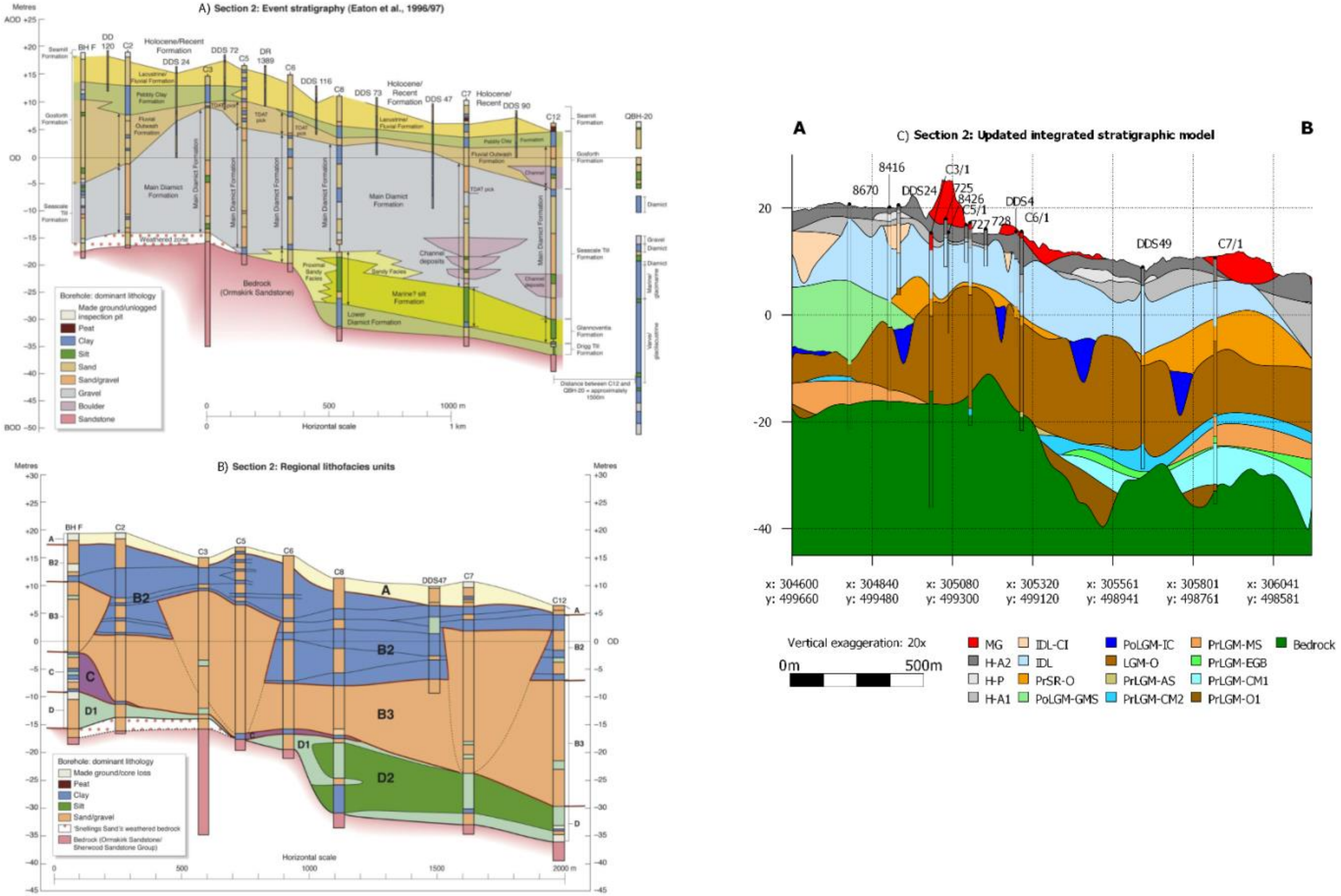


Figure 3.16: Comparison of previous interpretations: a) Section 2, Eaton et al. 1996/1997 [35, 58], b) regional lithofacies sections reproduced from Michie et al. 2010 [31], and c) the updated integrated stratigraphic model [21]. Figures placed side by side to allow comparison.

Section 3 is roughly parallel to the coast and lies south-west of the LLWR site boundary, extending from borehole F in the northwest to borehole A in the southeast, as shown in Figure 3.14. A comparison of iterations of Section 3 is shown in Figure 3.17.

Similarly to Section 2, Section 3 shows that the Holocene deposits have been represented in more detail in the updated geological model. The dunes that are present immediately behind Drigg Beach and along the spit are shown in the section in purple. The depth of the Holocene sequence is also shown to be deeper on the right side of the section in borehole A. The increased depth of the Holocene deposits is supported by the geophysics, which shows a deeper feature in this area that may represent the former course of the River Irt prior to formation of the spit.

Deeper in the sequence, Eaton et al. [35, 58] and the BGS lithostratigraphic units split the thick sands and gravels into two main units, the Main Diamict Formation or Holmrook Till and the Fluvial Outwash Formation or Barn Scar Sand and Silt. The regional lithofacies model groups these units into the B3 lithofacies unit, however splits out clays and silts within the Main Diamict/Holmrook Till into lithofacies unit C. In the updated geological model, the Fluvial Outwash/Barn Scar Sand and Silt is mostly re-interpreted as Post LGM Sands to represent the generally sand dominated unit. The deeper parts of the sequence that are more sand and gravel dominated are interpreted as LGM Outwash. Clay layers, split out into unit C in the lithofacies model, are interpreted as Post LGM Infilled Channels, consistent with the isolated extent and channel forms in geophysics.

As in Section 2, the deepest units, the Lower Diamict Formation, Maudyke Till, Glanoventia Formation and the lithofacies unit D, are split out into the Pre LGM sequence in the updated geological model. The distribution of the Pre LGM units in the updated model is quite similar to the regional lithofacies model as they follow variations in lithology. The Glanoventia Formation of the BGS lithostratigraphy is roughly consistent with the Pre LGM Coastal Mud and Pre LGM Sands.

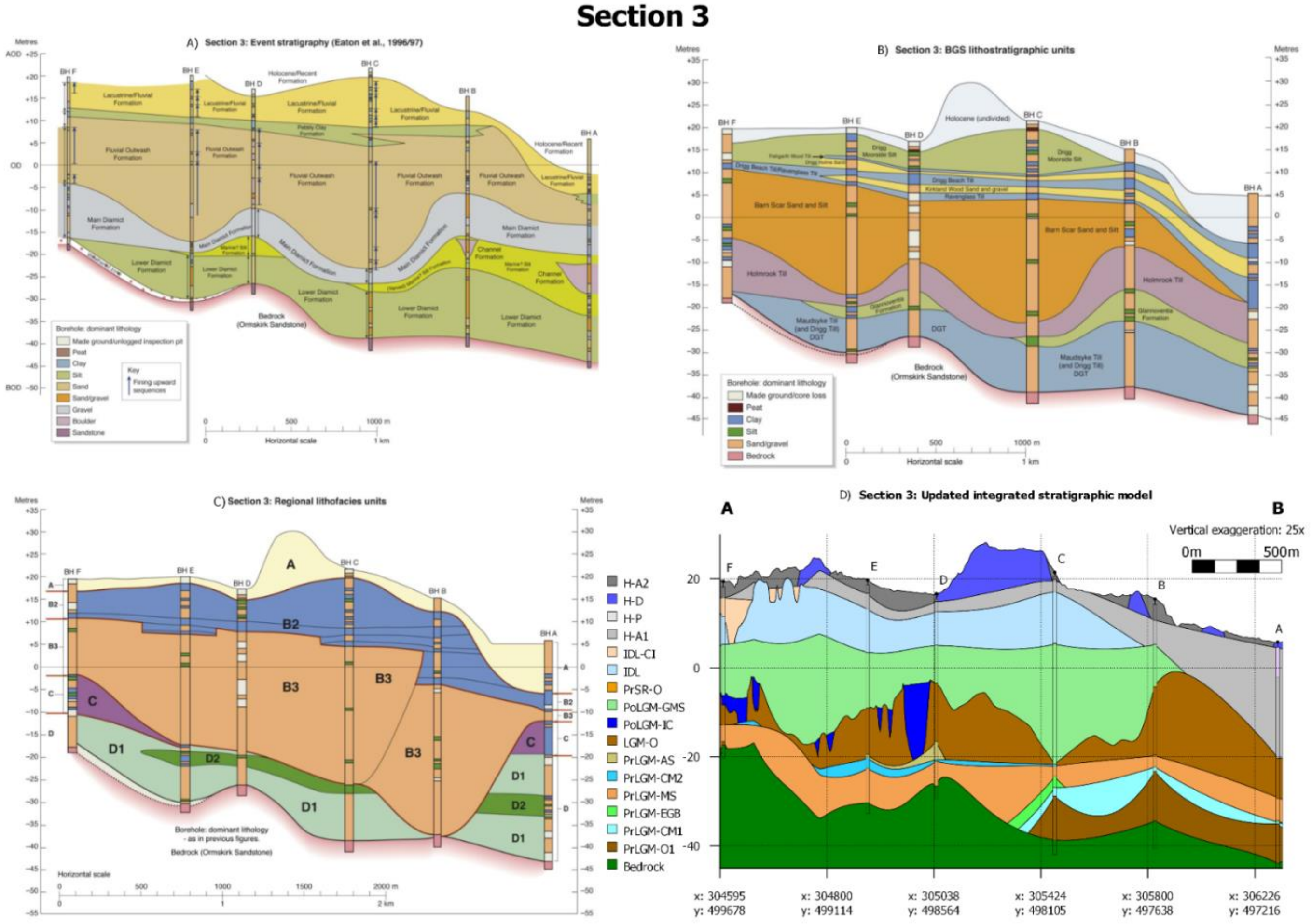


Figure 3.17: Comparison of previous interpretations: a) Section 3, Eaton et al. 1996/1997 [35, 58], b) BGS Merritt and Auton 2010 [59], c) regional lithofacies sections are reproduced from Michie et al. 2010 [30]and d) the updated integrated stratigraphic model [21]. Figures placed side by side to allow comparison.

3.2.3.2 Regional Bedrock Model

Underlying the Quaternary units, the bedrock model defines the base surface for the site and regional Quaternary geological models and represents the variation in the bedrock, including large-scale faulting. Oblique views of the bedrock model are presented in Figure 3.18 and Figure 3.19, with an additional cross-section shown in Figure 3.20. Development of this model was particularly important for understanding the potential implications of bedrock structures (particularly large-scale faults and channels) on groundwater flow, boundaries to flow and the distribution of the overlying Quaternary sequence. Additionally, an understanding of the bedrock contributes to a partial understanding of sediment provenance and thus ice flow.

To effectively represent these structures and identify provenances, seven distinct stratigraphic units have been modelled including the older Ordovician Borrowdale Volcanic Group and Lake District Felsic Pluton inland of the LLWR site, four separate formations belonging to the Sherwood Sandstone Group (Triassic), and offshore, a single stratigraphic unit representing the Mercia Mudstone Group (Figure 3.18). A significant unconformity is represented between the Ordovician igneous complexes and younger Permian-Triassic sedimentary sequence, which are separated by the Lake District Boundary Fault zone (Figure 3.19). Offshore, formations of the Sherwood Sandstone Group and the Mercia Mudstone Group are offset by a series of faults subparallel to the coast. Quaternary tunnel valleys (i.e. the Coulderton Channel and Madeline Channel) are shown as incisions in the bedrock surface (Figure 3.20).

Although large-scale features have been represented in the bedrock rock model where possible, the 3-D model is a simplified representation of the system. Representation of additional faulting and more detailed variation in bedrock stratigraphy has been limited to mitigate the introduction of additional uncertainty stemming from differences in the level of understanding of the bedrock across the region. A consistent level of detail has therefore been maintained in the bedrock model.

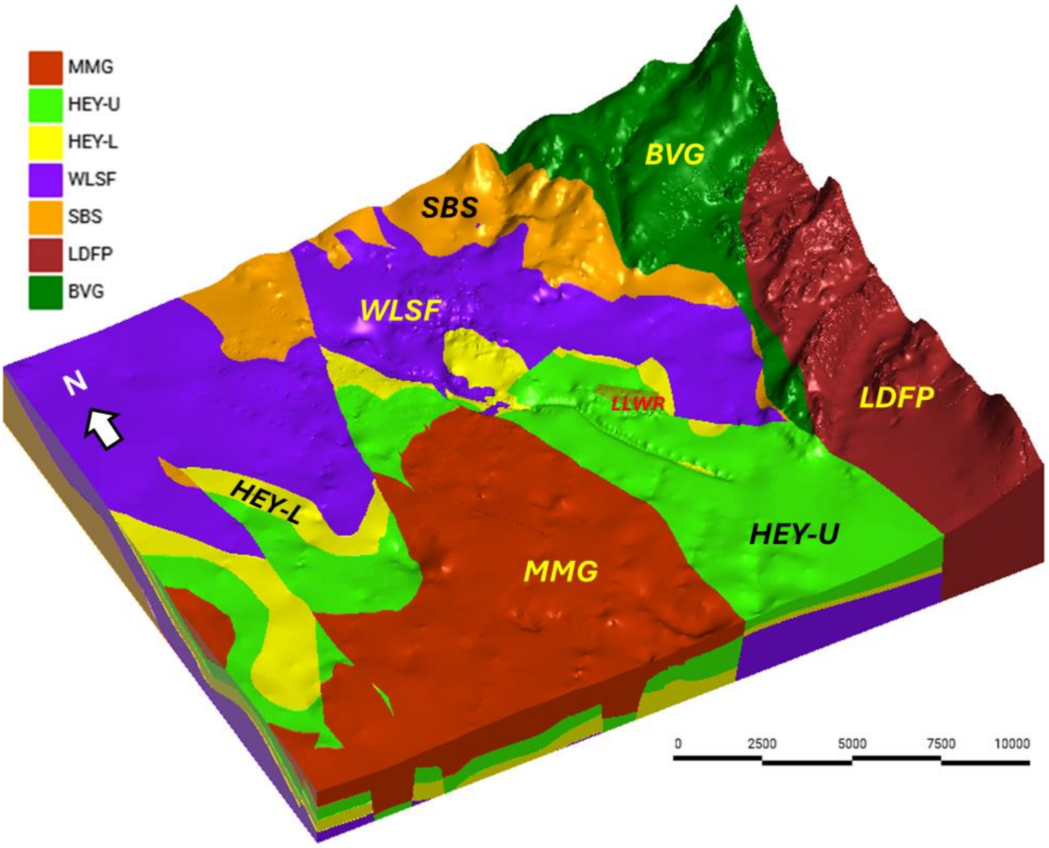


Figure 3.18: Oblique view of the regional bedrock model [21]. Leapfrog visualisation Vertical Exaggeration x5. Borrowdale Volcanic Group (BVG, dark green), Helsby Sandstone (lower) (HEY-L, yellow), Helsby Sandstone (upper) (HEY-U, light green), Lake District Felsic Pluton (LDFP, dark red), Mercia Mudstone Group (MMG, red), Chester Formation (St Bees Sandstone) (SBS, orange), Wilmslow Sandstone Formation (WLSF, purple).

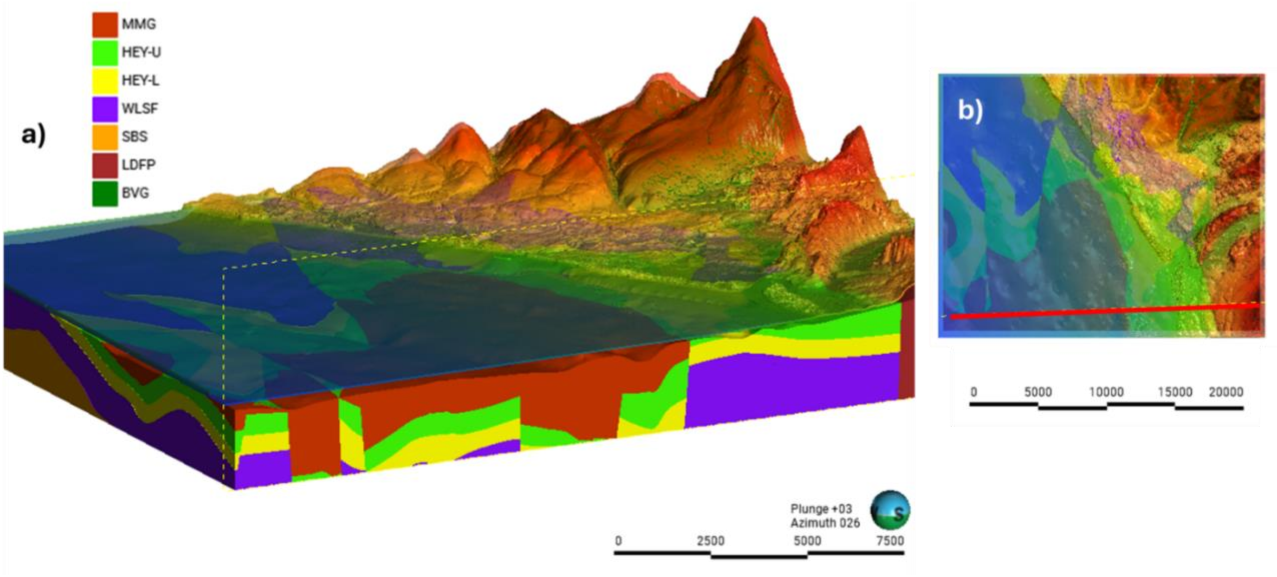


Figure 3.19: Oblique view of the regional bedrock model [21], Leapfrog visualisation, Vertical Exaggeration x5: a) block model with bathymetry surface overlay; b) location map.

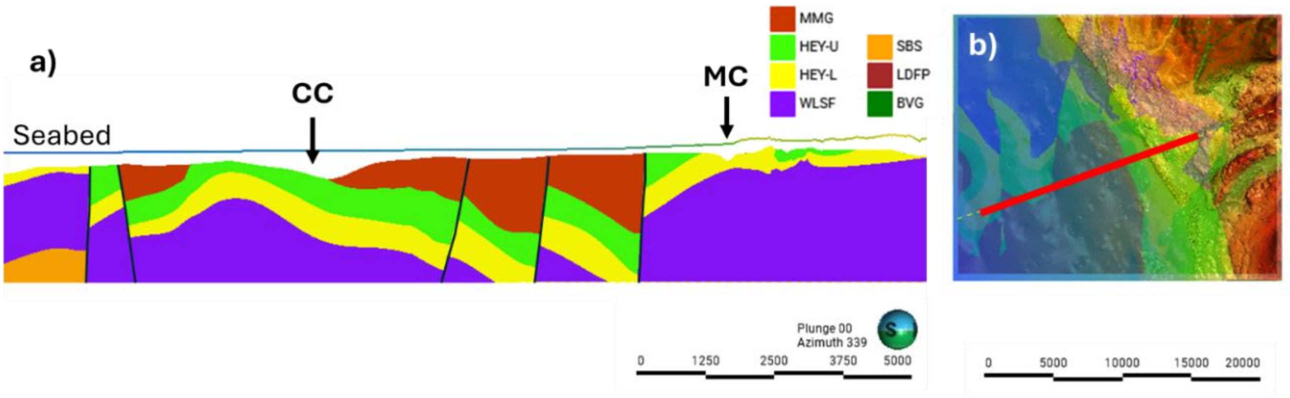


Figure 3.20: ENE trending cross-section through the regional bedrock model [21] showing incised Quaternary tunnel valleys Coulderton Channel (CC) and Madeline Channel (MC) cut into the rockhead: a) cross-section, Vertical Exaggeration x5, b) location map.

3.2.3.3 Regional-scale Quaternary Model

To understand the processes operating at the site scale and to produce sufficient input to the hydrogeological models, we need to consider the wider regional context. The resulting 3-D representation of this work is shown in plan in Figure 3.21 and as a cross-section in Figure 3.22. The figures illustrate the distribution of the 19 Quaternary units identified across the west Cumbrian coastal lowland study area. More detail on the development of the regional scale model is provided in the geological conceptual model report [21] and the geological modelling report [22].

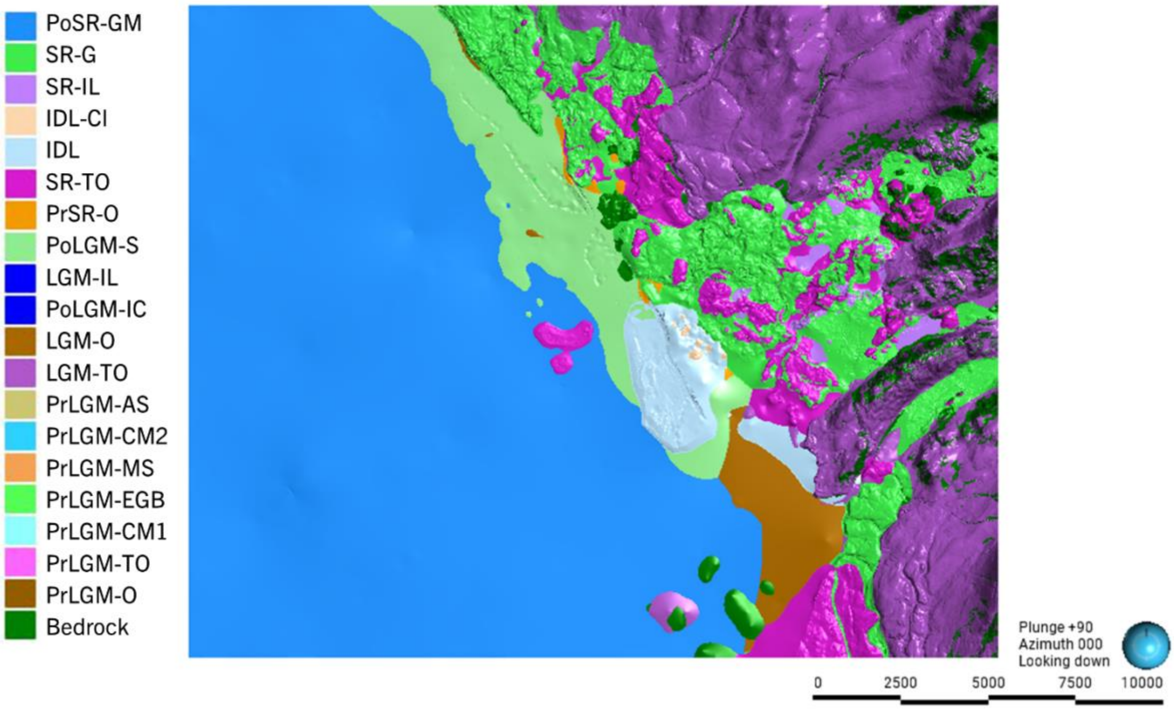


Figure 3.21: Map view of the Quaternary regional model. Note that the Holocene unit has been removed in this image. Leapfrog visualisation [21].

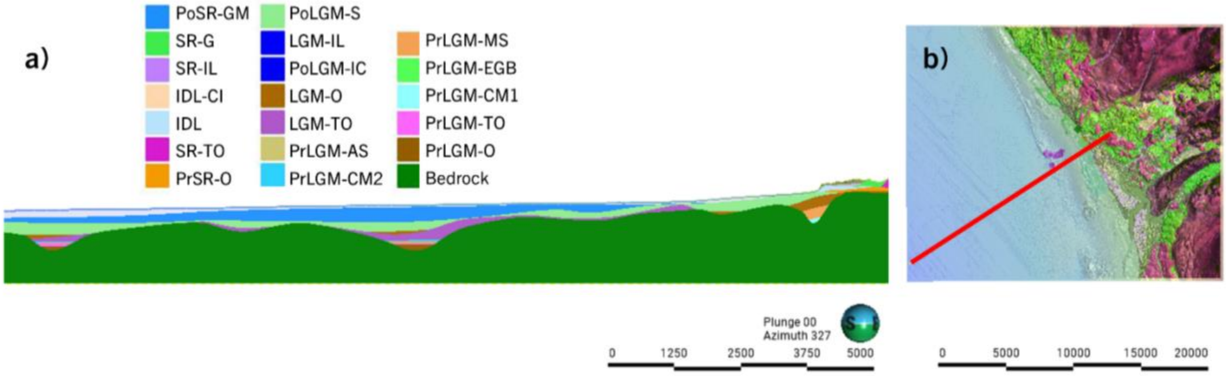


Figure 3.22: NE trending cross-section through the Quaternary regional model. Note the various tunnel valleys on this section which deeply incise into bedrock. A) Cross-section, b) Location map. Leapfrog visualisation, vertical exaggeration x10 [21].

3.2.4 Uncertainty in Conceptualisation and 3-D Digital Geological Model

Uncertainty in the stratigraphic framework and 3-D geological model arises from both observational and conceptual factors. Limited or poor quality data, particularly for older units, and ambiguity in interpreting depositional processes contribute to these uncertainties. While iterative, data-driven approaches and combined event stratigraphy and lithofacies methods have reduced uncertainty, challenges remain in assigning deposits to the correct stratigraphic event and representing heterogeneities. To simplify modelling, some units with complex internal variability have been grouped, which introduces representation bias but is considered to be preferable to over-segmentation. Additional uncertainty stems from software limitations that enforce sequential stratigraphy, preventing accurate depiction of contemporaneous deposits.

Figure 3.15 to Figure 3.17 show that there has been changes in the geological interpretation over time. While these are useful as a tool to visualise differences in the models, the production of the sections must be considered when comparing them; the previous sections were manually drawn while the updated section is a direct output from the 3-D digital geological model. Comparison of the sections shows that the broad trends of lithologies, layered clays, sands and gravels, are unchanged over time, but that the details have evolved as more detailed data have been collected.

Overall, these uncertainties influence geological interpretation and unit connectivity within the 3-D geological model, though mitigation measures aim to ensure a robust conceptual basis for hydrogeological assessments. How uncertainty in the geological conceptualisation and modelling has been considered in terms of the assessment models is covered in Subsection 5.3.

The geological model will be maintained, throughout the operational period, and periodically reviewed to take into account any new developments in the geological understanding of the site and wider area.

3.3 Contaminated Land Investigations

Understanding the extent of contaminated land at the LLWR is considered important to be able to satisfy both the GRA (Requirement R11) and GRR (Requirement R8), and to support the development of the Waste Management Plan (WMP) [10], which sets out how all radioactive and non-radioactive waste at the site will be managed. The LLWR site has a complex history involving a range of potentially contaminating activities, including explosives manufacturing, radioactive waste disposal, and the storage of hazardous materials. Assessing the nature, extent, and distribution of contamination is essential to ensure that any risks to human health, site workers, and the surrounding community are properly identified and managed.

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 or ground contamination that results from an authorised discharge. Land contamination may have resulted from the following.

- Contamination 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. The majority of these operations were carried out 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.
- 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).
- Contamination from management of stream sediment discharges prior to 1991.
- Leakage from the LLWR leachate management system.
- Road and rail use (fuel spillage, oil leaks etc).

The release of leachate from the vaults and trenches is specifically permitted for disposal or contained within a managed system.

A range of data collection and investigation methods were used to assess the potential impact of historical activities at the LLWR site. The process began with the review of multiple sets of aerial photographs, spanning from 1940 to 2020. These images were carefully examined to identify changes in site operations and land use over time, and to corroborate anecdotal evidence regarding site activities. To supplement the photographic record, recall interviews were conducted with individuals who had a long history of working at the site. These interviews provided valuable insights into undocumented or poorly recorded historical activities, helping to fill gaps in the official record. Historic records and technical drawings from the ROF era were also analysed. These included process schematics and building descriptions sourced from Ministry of Defence archives. The information obtained from these documents was used to identify the likely locations and types of potential contaminants associated with past industrial processes.

Radiological surveys formed a key part of the investigation. Large area gamma spectrometry surveys were conducted using high-resolution equipment to detect and map radiological features across the site. These surveys targeted areas such as the rail sidings, magazine compounds, and site perimeter. Portable detectors (e.g. NaI detectors with GPS) are used to support ongoing construction and maintenance activities and to delineate radiological features in the ground.

In addition to providing information for the geology and hydrogeology, the multiple borehole drilling campaigns have provided detailed information on the vertical and horizontal distribution of contaminants. Surface soil sampling has been carried out across the site to provide data on the extent of contamination. Phase 1 consisted of taking soil samples from across the site, on a 30 m grid pattern, during February and March 2013. The samples were collected from an approximate depth of 0.2 m below ground level. The second phase of the investigation was conducted in November and December 2014. During the second phase, 131 samples were collected from 1.0 m below ground level on a 60 m grid pattern across the site. The soil samples were analysed for radiological and non-radiological contaminants (metals, explosives residues, volatile and semi-volatile organics, Total Petroleum Hydrocarbon bands (C6-C20), pesticides, chlorinated organics, and asbestos). Additional radiological analysis was carried out for common radioisotopes and naturally occurring radioactive material where surface soils were observed to have elevated total alpha activity concentrations.

The environmental monitoring programme (see Subsection 4.1) is also used to understand contaminated land. This includes regular sampling and analysis of groundwater, surface water, and air to detect any migration of contaminants and to inform the ongoing risk assessment and management process. Both radiological and non-radiological contamination from several sources has been identified at the LLWR. In many locations, one type of contamination tends to be predominant; however, radiological and non-radiological contaminants frequently occur together.

In 2015, a land contamination risk assessment was produced [60] 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 [61]. This information has been used to inform monitoring requirements. The land contamination risk assessment was updated in 2022 and is recorded in the Site Characterisation Report [61] alongside information on the potential sources and investigations. The assessment indicated that only a small proportion of samples (0.03%) that exceeded the Suitable for Use Levels (S4UL) 'Commercial' criteria, for the current land use. In addition, 0.06% exceeded the 'Public Open Space Park' (POSpark) land use scenario. Lead was found to exceed the S4ULs at various depths in many of the zones. All of the Commercial and POSpark S4UL exceedances were due to lead contamination associated with ROF activities. The lead exceedances were identified at various depths in many of the zones. The spatial distribution of the lead exceedances appears to be related to the position of the ROF pipelines. Whilst it is recognised that the use of generic S4ULs may cause the screening values to be unnecessarily restrictive, there is not currently considered to be any impetus for conducting a site-specific detailed quantitative risk assessment. Current site management processes [62, 63, 64] are considered to be sufficient to effectively minimise any risk posed to human health.

The assessment [61] found it unlikely that enough contaminated soil could be disturbed to surpass Low Consequence Methodology safety thresholds. In addition, it was calculated that an operator would need to work for over 400 hours, in areas containing the maximum encountered activity in soils, which again is not deemed credible. This assessment supports the conclusion that the human health risks associated with radiologically contaminated land at the LLWR are low.

We have recently produced a Land Quality Register that sits within our management system. It supersedes Site Characterisation report [61] 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 3.23. 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.

It is known that asbestos was used widely in the construction of the ROF buildings and infrastructure. As a result of the demolition of the ROF structures, asbestos has been encountered across the LLWR site. In some of these areas, the accessible surface/near surface asbestos was removed, however, it is likely that residual below ground asbestos remains. Where work is planned to be undertaken in areas containing asbestos, appropriate PPE and RPE equipment is used and, where appropriate, a licensed asbestos contractor is present.

The findings of the quantitative risk assessments identify that the risks from contaminated land at the LLWR are low given the current land use and management procedures that are applied.

Remediation of contaminated land at LLWR has focused on targeted actions in areas where contamination posed a potential risk to human health or the environment, as identified through site investigations and risk assessments. These include:

- Between 1977 and 1984, drummed PCM was removed from five of the former ROF magazines and either transported to Sellafield or placed in a purpose-built store. Later investigations in the 1990s addressed water ingress and potential contamination beneath magazines. Soil from the areas where magazines were demolished was used for capping Trench 7, following assessment and management of any residual contamination. Removal of PCM from the remaining five magazines and decontamination was completed in 2019. The magazines are now awaiting demolition. This will allow further investigation of the ground under and around the buildings to determine whether further remediation is required.
- The B749 slab, historically used for temporary storage of radioactive materials, underwent surface decontamination trials using chemical agents. Although initial

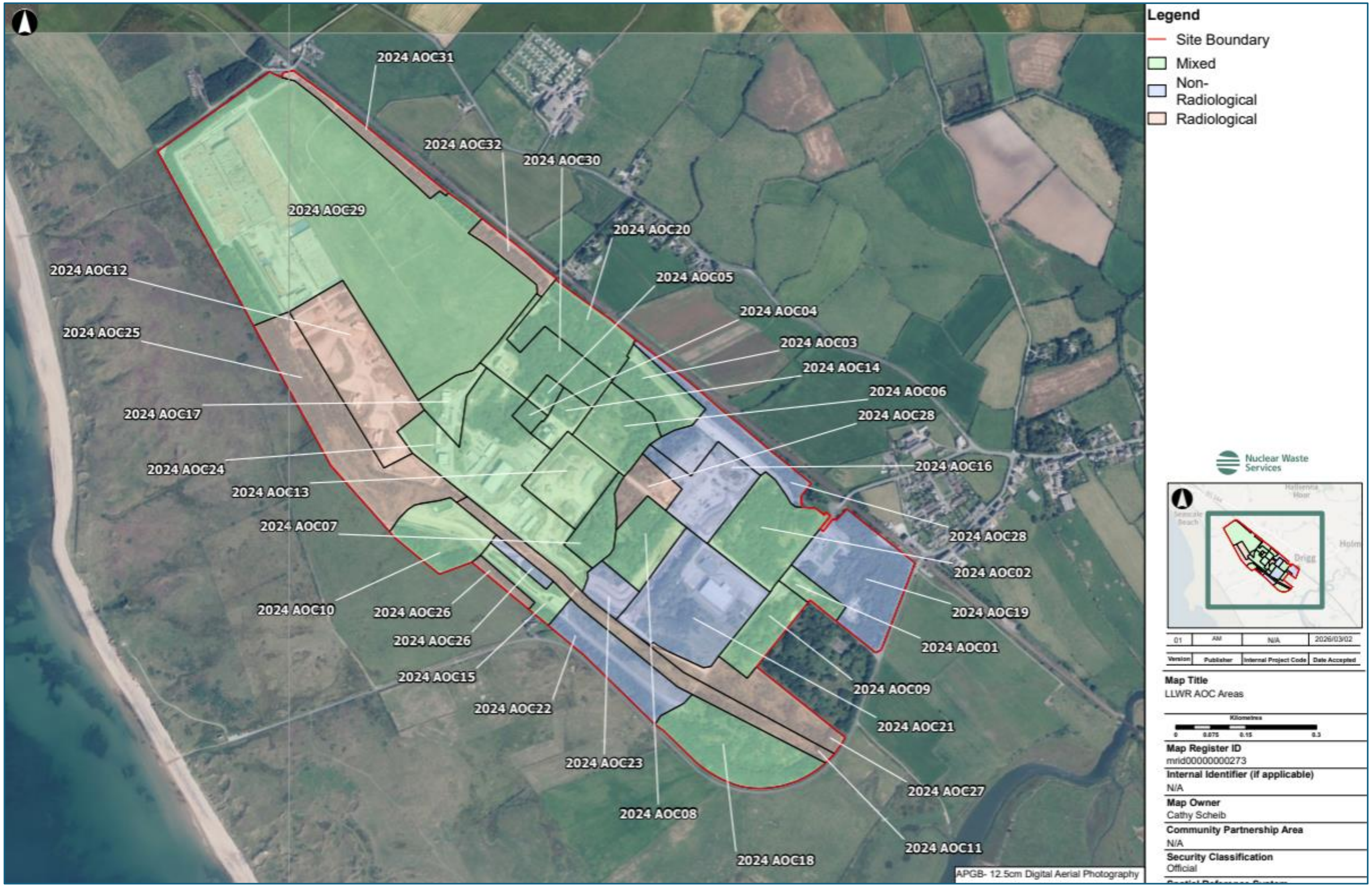


Figure 3.23: LLWR site with areas of concern (AOCs) for radiological, non-radiological and mixed contamination

trials removed a significant proportion of surface radioactivity, complete decontamination was not achieved, and further migration of radionuclides into the slab was suspected. Radiologically contaminated TNT has previously been identified in the ground within the B741 bunded area. Although this material was successfully removed and disposed of, it is suspected that further radiological contamination, TNT and related TNT decomposition products are present in the ground within the bunded area. Forward plans for remediation of both B741 and B749 slabs have been produced, with ongoing controls and restricted access in place.

- Remediation of the south bank of the East-West Stream was carried out in 2021 after elevated levels of Am-241 and Pu isotopes were detected. Approximately 110 m^3 of contaminated soils were removed prior to construction works. Localised remediation has also been undertaken along the banks of the Drigg Stream, where contaminated sediments from historical leachate disposal were found. In remediated areas, contaminated material was typically found within the top 500 mm of soil.
- Surface and near-surface asbestos identified during site investigations has been removed in accessible areas. Areas with larger volumes of asbestos are fenced off, and ongoing management includes updating hazard maps and restricting access.
- During construction works in the area, explosives residues were uncovered when excavating structures linked to the former TNT washing and finishing plant. Once exposed, these materials caused red discoloration of water in the immediate area. Laboratory analysis identified the presence of TNT and picric acid in the water, confirming contamination from historic ROF activities. Given the unacceptable risk of environmental impact from the migration of TNT and its breakdown products, a remedial plan was developed. In the summer of 2021, approximately 110 m^3 of contaminated soils were removed from the area prior to construction of drainage features and the haul road. Additional gamma and radiological surveys were conducted to ensure no further unusual radiological features were present. The remediation of P29 and its surroundings was risk-based and targeted, focusing on removing contaminated soils and managing the risk of explosives residues and associated chemicals. Ongoing monitoring and further investigation are planned to ensure the area remains safe for future use.
- Fluorescein dye was encountered around building foundations during the construction of the Stockpile C running surface. A manager's report of the ROF operation [65] suggests that fluorescein dye, from WWII pilots emergency packs, was mixed with water in the ROF TNT cleansing plant (Building P29) prior to its use in tidal tracer tests to support development of nuclear facilities at Sellafield. Although building P29 is not found within this area, it is possible that the record is incorrect, and the fluorescein was actually mixed in the other TNT cleansing plant, which is in an area that is now used for storage of soils and/or aggregates for capping operations. A running surface has been installed over the existing ROF foundations

and drainage with a membrane placed between the previous ground and running surface in order to prevent cross contamination of the running surface.

The Land Quality Register is an internal system used to record and manage contamination information across the site. It is used to track contamination issues by area, using a structured system that supports integration with GIS databases for spatial analysis. It captures both radiological and non-radiological contamination, ensuring a comprehensive understanding of site conditions. The register is linked to the WMP, with the aim of enabling:

- estimation of investigation effort and potential waste volumes;
- prioritisation of areas for remediation, investigation or monitoring;
- documentation of optimisation decisions and contamination remaining on site at closure.

It is noted that the agreed end state [66] for the site is for ecological/recreational use and that appropriate assessment criteria will be applied to determine whether remediation is required for each of the areas identified.

Additionally, the site must comply with requirements for the safe management of asbestos and contaminated land, as outlined in internal NWS procedures [62, 63, 64, 67] . These procedures mandate a tiered approach to risk assessment and control, including restricted access, control of excavations, management of excavated spoil, and mapping of known hazards. Hazard maps are used to record locations of specific hazards (e.g. radiological contamination, asbestos, unexploded ordnance), updated regularly based on investigation findings.

3.4 Mineral Resources

A review of the mineral resources in the vicinity of the site was carried out as part of the 2002 PCSC [68]. There have been no new mineral extractions commissioned or planned in the intervening period. The review noted that exploitation of mineral resources from the west Cumbrian coastal plain has occurred throughout the period of human history and particularly during the three previous centuries. However, economic reserves of the principal minerals, namely coal, hematite and anhydrite, became exhausted during the latter half of the twentieth century and resource extraction at the present time is generally limited to crushed rock, natural aggregate and sand. Current resource extraction in the immediate vicinity of the site is confined to a sand and gravel operation at Peel Place, approximately 3 km north-east of the site. Historically, glacial till has been excavated on a small scale near Drigg for local brick and tile manufacture. Shallow deposits of recent blown sand have also been worked, presumably for similar construction purposes, and large quantities of pebbles were removed from Drigg Beach for shipping ballast in the nineteenth century [69].

Of the geological formations present within the vicinity of the site, several could be considered to be resources for potential future exploitation:

- Quaternary deposits (aggregate/clay) are currently exploited elsewhere and it is considered unlikely that the deposits at LLWR would be extensive enough to allow economic operations.
- Triassic Sandstone (building stone) underlies the entire coastal plain and would be more easily quarried elsewhere where it crops out at the surface.
- Hydrocarbon reservoirs in the Irish Sea Basin are hosted by Triassic sandstones, but these formations are unlikely to be productive in the Drigg area due to the lack of suitable organic-rich source rocks in the underlying Carboniferous strata.
- The Carboniferous Limestone subcrop is projected to lie beneath the Triassic sandstones close to Drigg, at a depth of 1200 m to 1500 m. This particular stratigraphic overstep appears to be linked to the development of hematite orebodies in the Egremont and Cleator Moor areas and could have controlled the development of similar mineralisation. The extreme depth, however, would render such occurrences uneconomic at the present time.

The BGS report on the suitability of the geology in West Cumbria for a deep disposal facility [70] considered the presence of natural resources as part of its exclusion criteria. This was updated as part of the assessment of the Mid-Copeland area [71]. The reports both indicated no economically viable resources in the vicinity of the site.

Given the available information, it is not considered likely that mineral extraction would be undertaken in the vicinity of the site under present conditions.

4 Hydrogeological Understanding

This section describes the hydrogeological setting by presenting the available hydrogeological data, the development of the hydrogeological conceptual model and the expected site evolution. As with the geology, the understanding of the hydrogeology of the LLWR site has developed as more data have become available from the site investigation programme and the monitoring programme. The aim has been to gain an overall understanding of the behaviour of the hydrogeological system so that the migration of contaminants in groundwater pathways can be represented in the safety assessment. It is noted that the environmental monitoring programme has developed over many years and that, as the majority of the data are only available from late 1980s, data are not available to establish baseline conditions prior to disposals commencing or prior to the use of the site as an ordnance factory. Up-gradient monitoring is used to establish baseline conditions as a surrogate.

A detailed review of the hydrogeological setting, the development of the hydrogeological conceptual model for the LLWR and supporting evidence is given in reference [23]. The existing monitoring programmes on climate, surface water and groundwater are summarised below. More details on the monitoring programme are provided in the '*Monitoring*' report [8].

4.1 Monitoring Programme

4.1.1 Climate

Climate is taken to mean the seasonal and longer-timescale variation in meteorological parameters, including during extreme events, particularly temperature and precipitation, to establish hydrological and meteorological boundary conditions and physical constraints on soil development and vegetation.

The present-day climate at the LLWR is classified as cool temperate. The prevailing wind is from a south-westerly direction. The mean annual temperature over the last several decades has been measured at 9.7 °C for the West Cumbrian coast and average annual precipitation from 1999 to 2024 was 1,150 mm. The seasonal variation around these annual means is illustrated in Figure 4.1. Temperature and precipitation are the key climate drivers for much of the ESC modelling of the surface environment at the LLWR.

The automatic weather station at the site provides details of precipitation, temperature, wind direction and speed, etc. In conjunction with stream flow data, the information is used to evaluate the effective rainfall for the site and aid in the quantification of the site water balance.

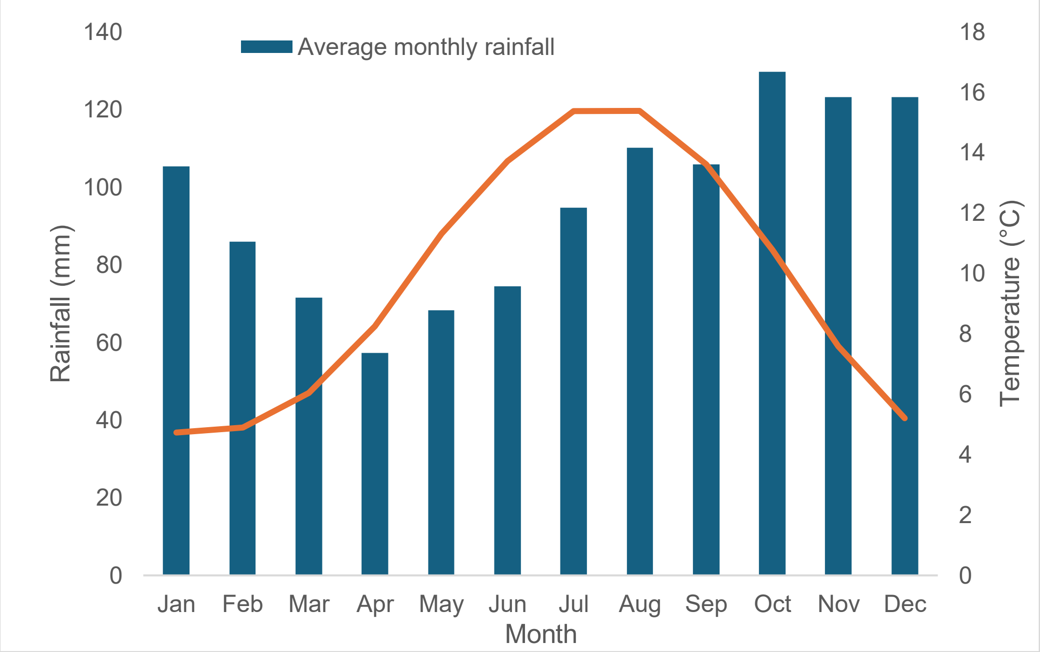


Figure 4.1: **Average monthly rainfall and temperature 1999 to 2024**

4.1.2 Surface Water

The surface and soil zone comprise the surface water hydrology including the River Irt, Drigg Stream and East-West Stream (see Figure 4.2), and the unsaturated zone. The processes of overland flow and interflow occur in this zone. The recharge to the underlying groundwater is the precipitation less the evapotranspiration, with overland flow and interflow taken into account.

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 and flow measurements 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. 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 (SuDS), including multiple lagoons to aid sediment removal. The SuDS system has been designed to be able to accommodate a 1-in-200-year flood event, with contingency[2].

There are a series of ponds on the SSSI to the west of the site. The water levels in these ponds have been monitored to determine whether they are a potential receptor. Combined with the groundwater level data from adjacent boreholes the ponds have been confirmed as being predominantly ephemeral and not groundwater-fed [72]. As such they are not considered to be a potential receptor.

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[2] Defined as a 1-in-200-year event "+20%".

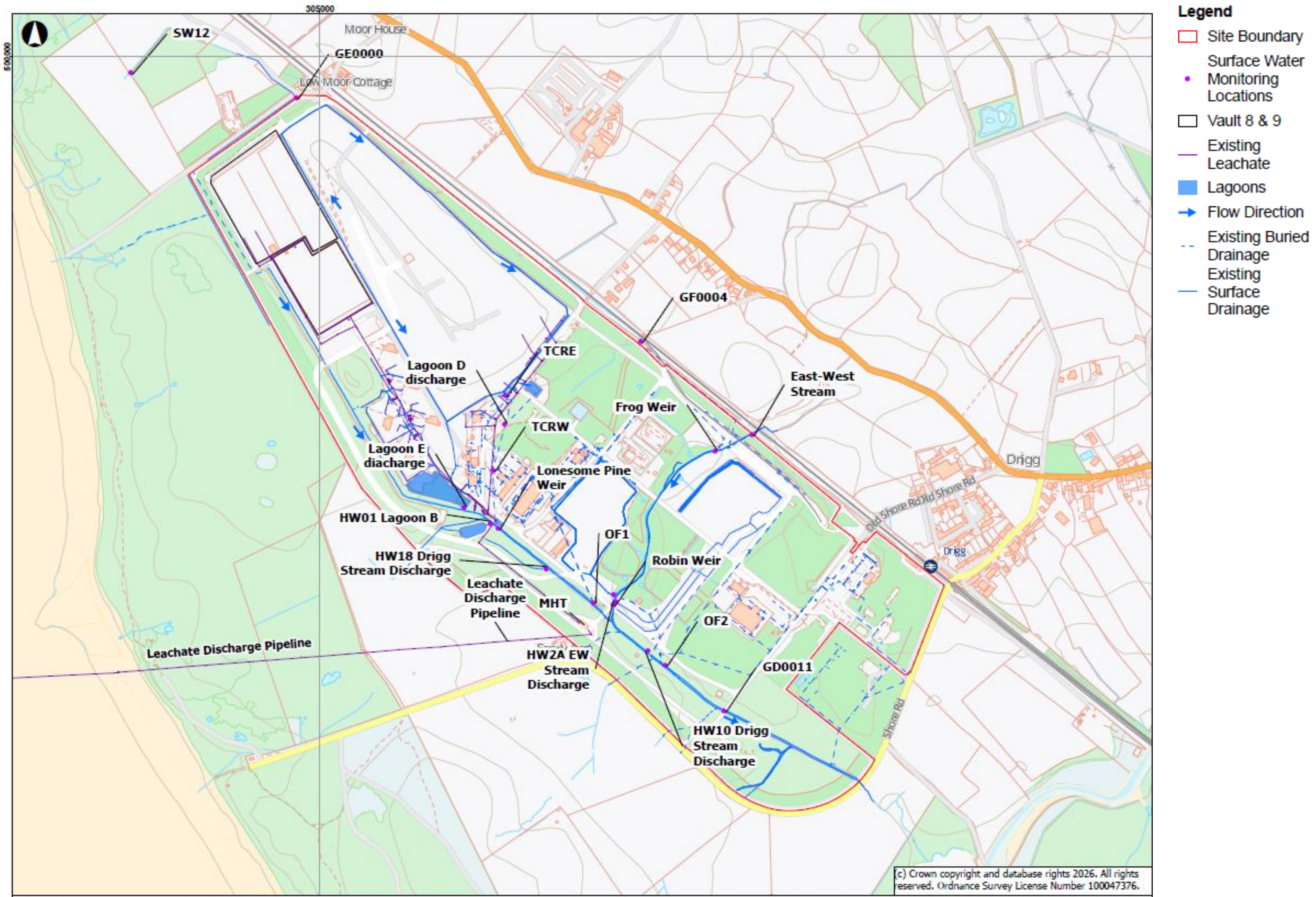


Figure 4.2: **Streams, surface water drains and leachate drains within and surrounding the LLWR**

4.1.2.1 Water Balance

Monitoring of water level and flow within each stream provides 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 to develop models of site hydrology [23]. Considerable work was undertaken to understand the site and regional water balances for the 2011 ESC [73, 74, 75]. The work has continued since 2011, particularly with regards to the water balance over the interim trench cap [76, 77, 78], which is used to assess engineered barrier performance [79] and consideration of how the catchment areas have changed from prior to the ROF construction and waste disposal operations [53]. The catchment areas for the trench cap perimeter drain are shown in Figure 4.3.

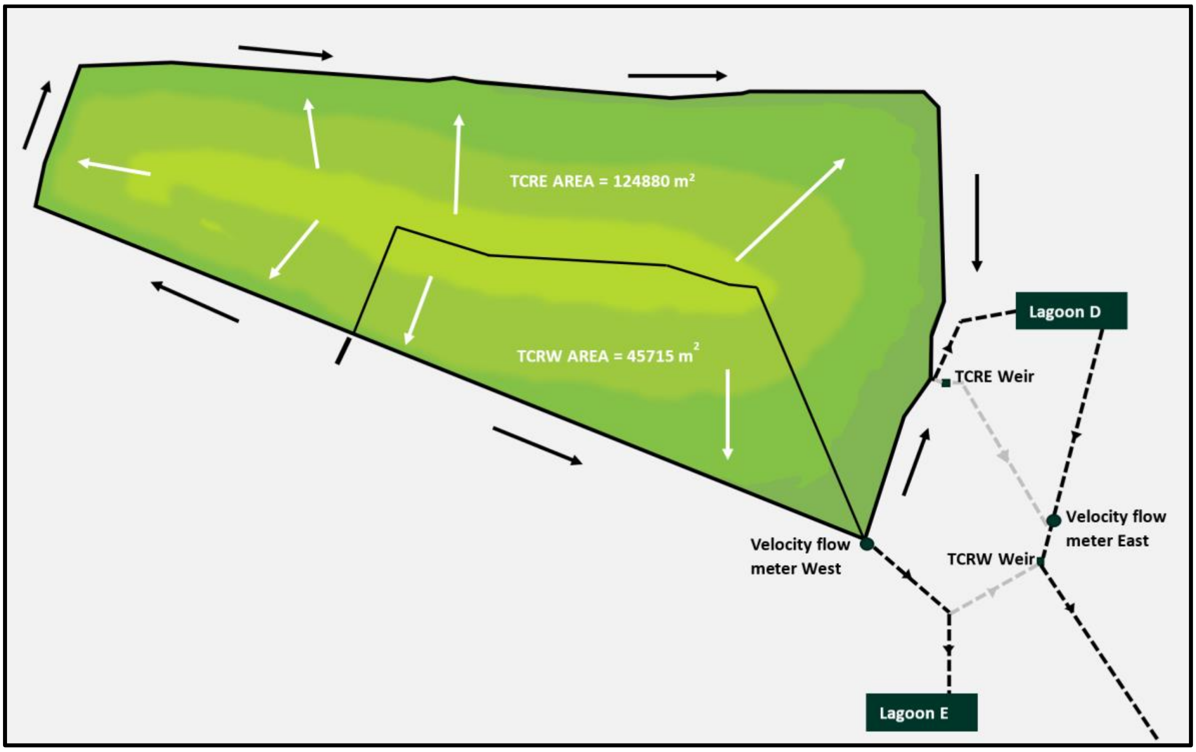


Figure 4.3: Trench cap catchment areas and relevant monitoring locations

Precipitation is an important factor determining recharge, but not all precipitation becomes recharge into the groundwater. Some precipitation evaporates or is taken up by plants and then given off as moisture vapour in the process of transpiration, collectively referred to as evapotranspiration; while some flows to the sea as surface water or in the uppermost soil layer, referred to collectively as quickflow. Hydrologically effective rainfall (HER) is defined by precipitation minus evapotranspiration. Precipitation can be directly obtained from the meteorological data whereas evapotranspiration calculations involve higher complexity. For the LLWR, estimation of HER is obtained using the LLWR WATBAL model [80], which uses the method of Penman-Monteith to represent the physical process occurring and calculate the potential evapotranspiration. In some circumstances (hot dry conditions), there may be insufficient water for evapotranspiration to occur at the potential rate. Models such as the Meteorological Office's MORECS model [81] can be used to calculate the actual evapotranspiration in such conditions. Given that conditions are very wet in Cumbria, it is assumed to be an acceptable approximation to take evapotranspiration to be equal to potential evapotranspiration in modelling for the LLWR. Averaged values of precipitation, potential evapotranspiration and HER for the LLWR are shown in Table 4.1 and Table 4.2.

The flow to the surface water bodies resulting from the precipitation event is generally split into two components: quickflow and baseflow. The quickflow component increases rapidly after the start of the precipitation event and then falls off rapidly once the event stops. The baseflow component increases more slowly than quickflow after the start of the event and falls off more slowly once the event stops. Quickflow is considered to correspond to the combination of overland flow of surface water and lateral flow of water within highly permeable soils adjacent to the surface. This component usually affects the short and fast flowing subsurface flow paths, i.e. very close to the surface. Baseflow is considered to correspond to water flowing down to the main water table and then flowing as groundwater flow beneath the water table to discharge at a stream or river. As such, the baseflow component is expected to provide the main contribution to recharge.

Recharge is defined by HER minus quickflow. For the LLWR, quickflow is obtained using the LLWR stream-routing model [74]. The stream routing model incorporates use of several constant parameters such as storage delay constants for the quickflow, slowflow and loss components and slowflow threshold storage. The local contribution to quickflow will vary over the catchment for the stream or river so values have been calculated for each catchment and then averaged in Table 4.1 and Table 4.2. The ratio of quickflow to HER varies across the year but remains broadly consistent year on year. Examination of historical quickflow data from the stream routing model [74] shows that quickflow remains as a consistent proportion of HER and only varies minimally with changes in HER, so the quickflow proportion is assumed to remain unchanged over time with 47% of HER [82].

4.1.2.2 Flooding potential

The potential for current day surface water flooding of the disposal area has been assessed by reviewing previous flood data and by looking at the Environment Agency’s flood risk assessment map [83]. As shown in Figure 4.4, the majority of the LLWR is located within Flood Zone 1 (land assessed as having an annual probability of river or sea flooding of less than 10^{-3}). There is a very low risk that this area will flood from the surface water features listed above. A small area extending from the River Irt to the southern end of the site is classified as Flood Zone 3 (land assessed as having an annual probability of river flooding of more than 10^{-2} and an annual probability of flooding from the sea of more than $5\ 10^{-3}$). The risk of surface water flooding is classed as very low at present and in the future (up to 2069). The surface water system has sufficient capacity to cope with extreme rainfall events without flooding affecting surface facilities. Flooding from the River Irt to the south may encroach on to the site following the line of Drigg Stream but the topography of the site means that the disposal area or surface facilities will be unaffected.

Table 4.1: **Monthly average precipitation (P), potential evapotranspiration (PE), HER and Quickflow from 2003 to 2021.**

	P (mm y^{-1})	PE (mm y^{-1})	HER (mm y^{-1})	Quickflow (mm y^{-1})
January	1,297	128	1,169	627
February	1,049	191	858	461
March	897	317	580	313
April	628	558	70	52
May	844	651	193	105
June	906	708	199	83
July	1,140	717	423	215
August	1,394	619	775	411
September	1,221	501	720	368
October	1,520	326	1,193	614
November	1,474	208	1,267	674
December	1,470	126	1,343	685

Table 4.2: Annual average precipitation (P), potential evapotranspiration (PE), HER and Quickflow from 2003 to 2021.

	P (mm y^{-1})	PE (mm y^{-1})	HER (mm y^{-1})	Quickflow (mm y^{-1})
2003	966	360	606	316
2004	1,064	412	653	346
2005	966	402	565	292
2006	1,198	464	734	389
2007	976	433	544	286
2008	1,096	405	690	366
2009	1,196	449	746	391
2010	992	400	591	310
2011	1,273	382	891	461
2012	1,378	317	1,061	556
2013	1,071	316	755	388
2014	1,199	467	732	391
2015	1,330	480	850	438
2016	1,238	436	802	428
2017	1,323	433	890	465
2018	1,144	435	709	374
2019	1,224	437	787	416
2020	1,176	493	683	358
2021	1159	499	660	338

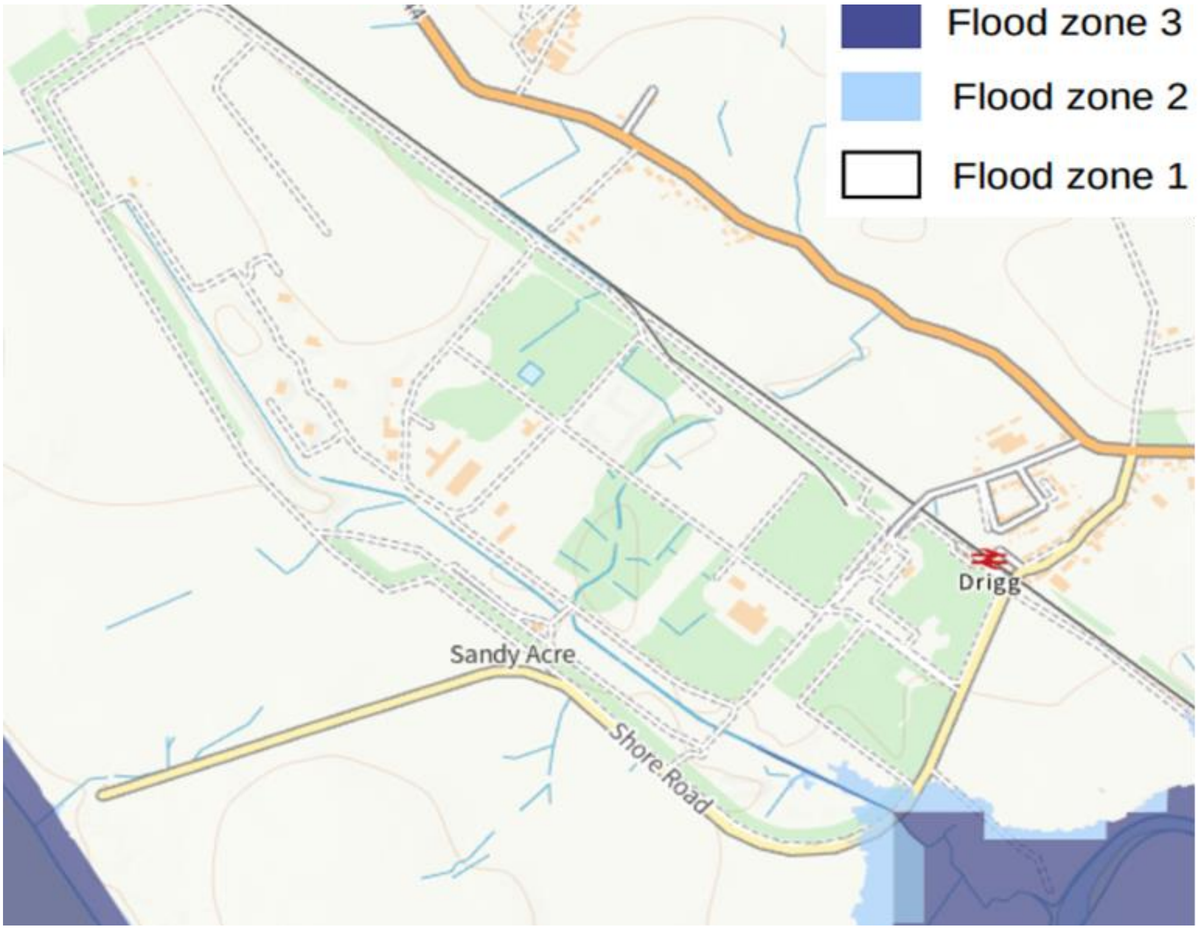


Figure 4.4: Flood risk areas at the LLWR [83]

4.1.3 Groundwater Monitoring

Groundwater level and quality data collected through the environmental monitoring programme are fundamental inputs for developing and refining the hydrogeological conceptual model at the LLWR site. Details of the groundwater monitoring programme are provided in the '*Monitoring*' report [8]. The current 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 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. Long-term groundwater head monitoring has been carried out in site and regional boreholes, including high-frequency logger installations, providing data on vertical and lateral head gradients and transient responses to recharge.

Figure 4.5: Groundwater level monitoring locations [84]

4.1.4 Key Groundwater Characteristics

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. Examination of the data sources suggests certain key characteristics of the groundwater flow which are described below.

There is a strong influence of lithology on the flow − in particular, the lithology of the Quaternary deposits. Hydrogeological properties are related to lithology and, in particular, to grain size. This has been confirmed through many measurements of hydraulic conductivity undertaken through both field and laboratory testing [49, 85, 86]. Slug tests and pumping tests were undertaken in Quaternary deposits and bedrock to estimate hydraulic conductivity over a range of spatial scales. Testing included measurements during drilling and post-completion tests in completed boreholes. Short- and long-duration pumping tests have been used to characterise more permeable units (notably sand and gravel outwash and upper sandstones), supporting identification of higher-permeability regional flow units.

A series of tracer tests have been carried out at the LLWR site since 1990 [87]. These have included using sodium fluorescein, potassium bromide, iodine-131, sodium chloride and rhodamine as tracers. They have generally been inconclusive as monitoring devices have often failed to detect the released tracers.

4.1.4.1 Subdivision of Groundwater System

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:

- The surface and soil zone.
- Upper Groundwater is present within the upper Quaternary deposits 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 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 is observed in monitoring wells with screen tops between 6 m OD and 10 m OD, which are screened in deep superficial deposits and the upper sandstone, are considered to lie in the Medium Groundwater.

  - Deep Groundwater is observed in 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.

Figure 4.6 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. For lower average screen elevations, the groundwater heads show significant variability but are not correlated with elevation.

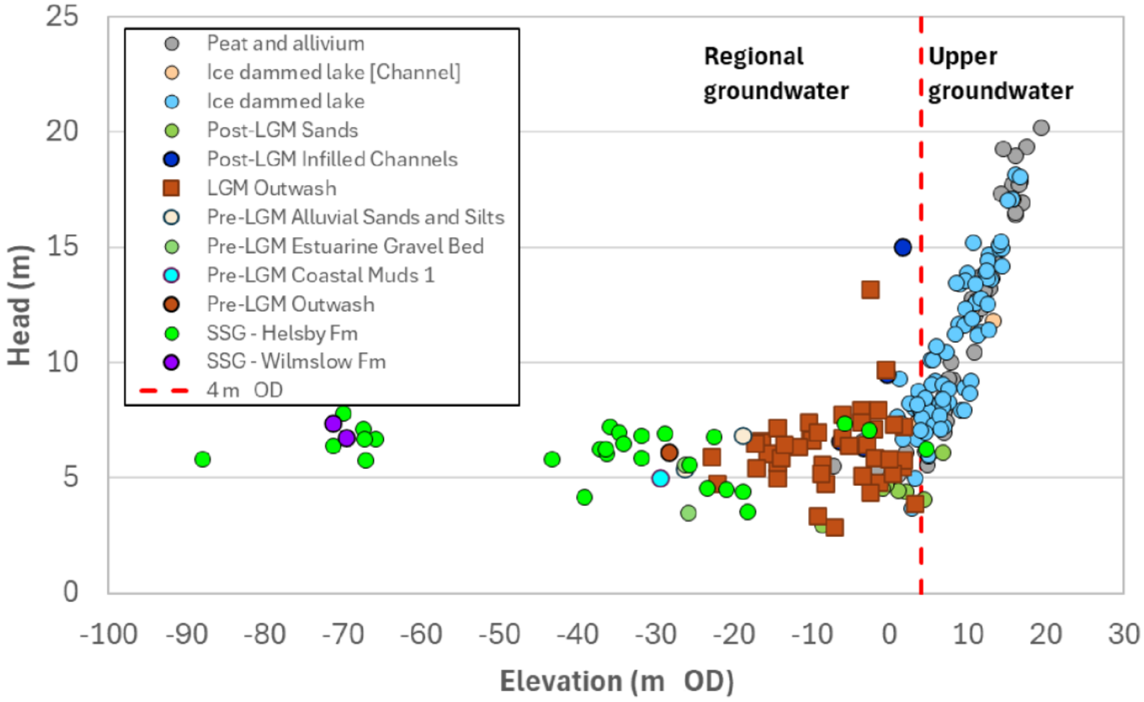


Figure 4.6: **The observed heads in the boreholes near the LLWR plotted against the elevation of the centre of the screened interval. The figure also shows the point at 4 m OD elevation, which is the approximate boundary between the Regional and Upper Groundwaters. The points are coloured according to the units for the geological model [23].**

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 predominantly vertical, and a lower zone 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. The two zones are therefore named the Upper and the Regional Groundwater. It is noted that transient head measurements in the Upper Groundwater show a faster response to rainfall than those in the Regional Groundwater.

In Figure 4.6, 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.

4.1.4.2 Position of the Water Table

Observations of small streams running in local topographic lows and the existence of many springs suggest that the water table is close to the ground surface (within a few metres) over most of the region of interest. The presence of the streams and springs suggests that groundwater is generally discharging to the streams and springs, and hence the water table is at the surface in these locations. In the regions of higher ground between the streams, the water table is higher than the levels of the streams, allowing groundwater to flow towards the streams, but below the ground surface. Some of the water flowing in the streams will have come from overland flow, or interflow which represents the lateral flow within the unsaturated region.

4.1.4.3 Direction of Lateral Groundwater Flow

Figure 4.7 shows that the head in the Regional Groundwater generally follows a trend with a decrease from inland towards the coast. The hydraulic gradient becomes much gentler at distances greater than about 1 km from the coast, as indicated by the trend line. The trend suggests that, generally, the flow in the Regional Groundwater is 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.

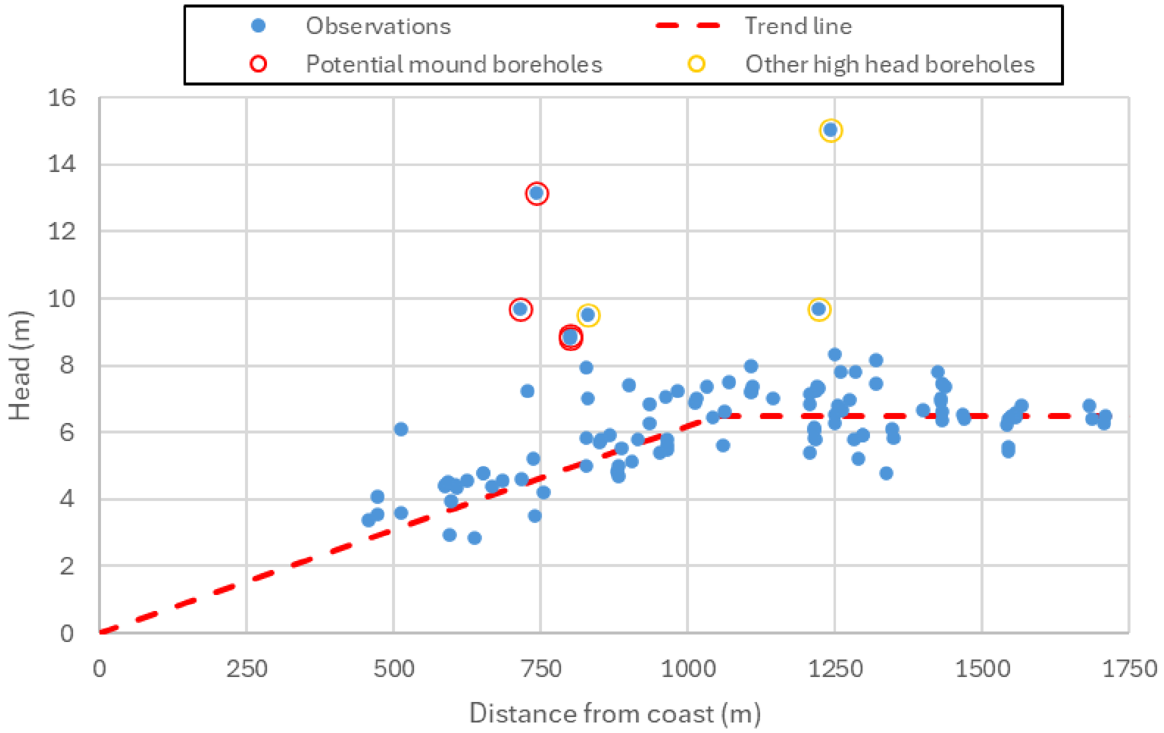


Figure 4.7: **The heads in the Regional Groundwater plotted against the distance from the coast. Outliers from the general trend, potentially associated with the groundwater mound, are circled [14].**

In Figure 4.7, 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 [75]. More recent data suggest there is more complexity than one single mound area, which is consistent with the understanding of 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 4.8 shows a contour plot of the groundwater heads with the outliers removed.

Previous studies have found no lithological reason for the groundwater mound [88], although the drilling method used (cable percussion) for the construction of the particular boreholes is not best suited for picking up small changes in lithology. Recent geological investigations have also noted the high degree of heterogeneity and channelised deposits within the outwash units, which is likely to add complexity to the groundwater system.

Over most of the region, the groundwater salinity is very low. This is because the system is an active near-surface system, with groundwater constantly being replenished by recharge of nearly fresh water from precipitation. However, near the coast, seawater will intrude into the groundwater system. This is due to the seawater being denser than freshwater. As a result, sea water flows under the fresh water and into the system. It is expected that saline water would only be present in the groundwater near the surface in the offshore area or within a very short distance from the coast. The primary effect of the seawater intrusion is that the saline water effectively acts as a no-flow boundary for flow in the fresh water region.

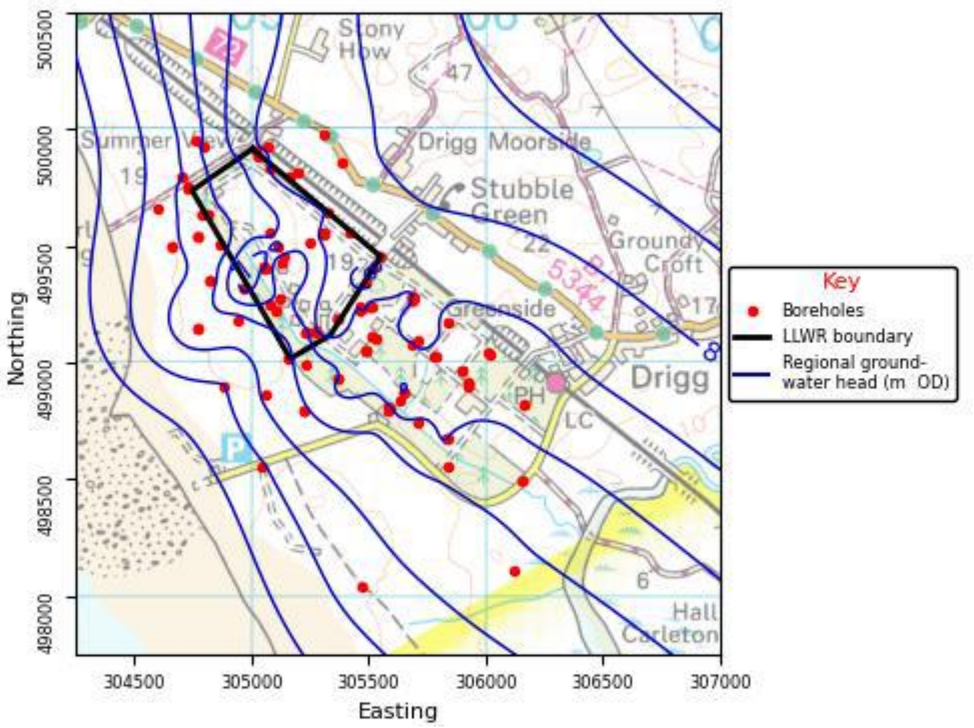


Figure 4.8: **Interpolated contours of the groundwater heads in the Regional Groundwater around the LLWR site (with outliers removed). The contours are at 1 m intervals [14].**

4.1.4.4 Groundwater Flow in the Bedrock

The groundwater flow in the bedrock is mainly in the upper part, with flow in the deeper bedrock being considerably weaker. This means that the flow in the region of interest is mainly in the upper 100 m of the geology, i.e. in the Quaternary deposits and the upper part of the bedrock. This understanding is derived primarily from temperature measurements collected from deep boreholes during the Nirex programme [89] in the 1990s. Vertical temperature gradients were fairly constant within each unit, except within about 70 m of the top of the sandstones. The change in temperature gradient suggests that in the upper part of the sandstones, advection (i.e. transport by flowing groundwater) makes a significant contribution to heat transport. For advection to have a significant influence on heat transport in the upper sandstones, the groundwater flows must be much larger than those in the lower rocks. This suggests that most of the groundwater flow in the bedrock occurs within the upper part.

4.1.5 Hydrogeochemistry

The 2011 ESC used the 2002 conceptual model for hydrogeochemistry [90]. A review of all the available non-radiological monitoring data [91] was carried out in 2010. The review established baseline water quality levels for water entering the site as rainwater, surface water or groundwater for comparison with water quality within and downgradient of the site.

To provide an update for the 2026 ESC, a review of groundwater chemistry data was carried out [92]. The review suggested that further major-ion data be collected across the site. This was carried out as part of the monitoring programme and the review was updated in 2019 [93]. The review was based primarily on groundwater data but also considered further data on rainwater and trench leachate compositions.

As an output of the review, it was concluded that LLWR groundwater is dominated by meteoric input, modified by ion-exchange processes and by equilibrium with calcite in some locations in the Regional Groundwater. Some limited mixing with deeper water is not ruled out. There is a lack of correlation of chloride concentrations in the Upper Groundwater with proximity to the coast that strongly suggests that there is no significant effect of sea-spray aerosol deposition in the area covered by the LLWR boreholes [88].

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.

Overall, the new analysis demonstrated consistent groundwater compositions that are broadly stable with time. 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 the baseline values derived during an extensive review of non-radiological water quality entering the site reported in 2026 [94]. Such comparison reveals that groundwater quality in the periods 2016 to 2020 and 2021 to 2025 is broadly consistent with that in the 2017 Hydrogeological Risk Assessment (HRA) [95]. This suggests no evolving risk posed to groundwaters due to release of non-radioactive contaminants from the site. Monitoring and assessment evidence shows that LLWR operations have not resulted in significant non-radiological contamination of groundwater [15, 96]. Where non-radiological substances are detected, concentrations are generally low, consistent with natural background levels, and not localised around the LLWR site.

However, it did note that at 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 wastes disposed of in the trenches.

Tritium, as tritiated water, is a useful tracer in groundwater because it behaves conservatively and is transported with groundwater at the linear flow velocity. Identification of tritium at monitoring locations provides an indication of the presence of a migration pathway for contaminants in the groundwater underlying the site. The tritium activity levels in the Upper and Regional Groundwater 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.

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 past 40 years (as shown in Figure 4.9), 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 4.9 to Figure 4.12. 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 has restricted 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 increased monitoring in areas of concern. Figure 4.9 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 monitoring points have been retained for groundwater level monitoring and remain available for future use if required.

The tritium levels remained relatively stable in more recent years, although there is an overall downward trend. The increased tritium concentration observed in the Medium Groundwater since 2013 is principally attributed to the elevated activities at boreholes 8420p1 (adjacent to Trench 3) and Fp1 (on the SSSI between the site and the coast). Tritium activity concentrations at both 8420p1 and Fp1 have reduced from their peaks in 2015 and 2016, respectively, as shown in Figure 4.13 and Figure 4.14. The unusual peaks in tritium observed at these locations is thought to be caused by 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 increased loading of 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.

Elevated tritium levels were historically found at a railway drain (GF0004) directly to the east of the LLWR site, as shown in Figure 4.15. The low tritium activity now at GF0004 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. Figure 4.15 shows three positive results that appear to be lower than previous non-detects. All laboratory analysis results are calculated in accordance with ISO11929 [97] 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.

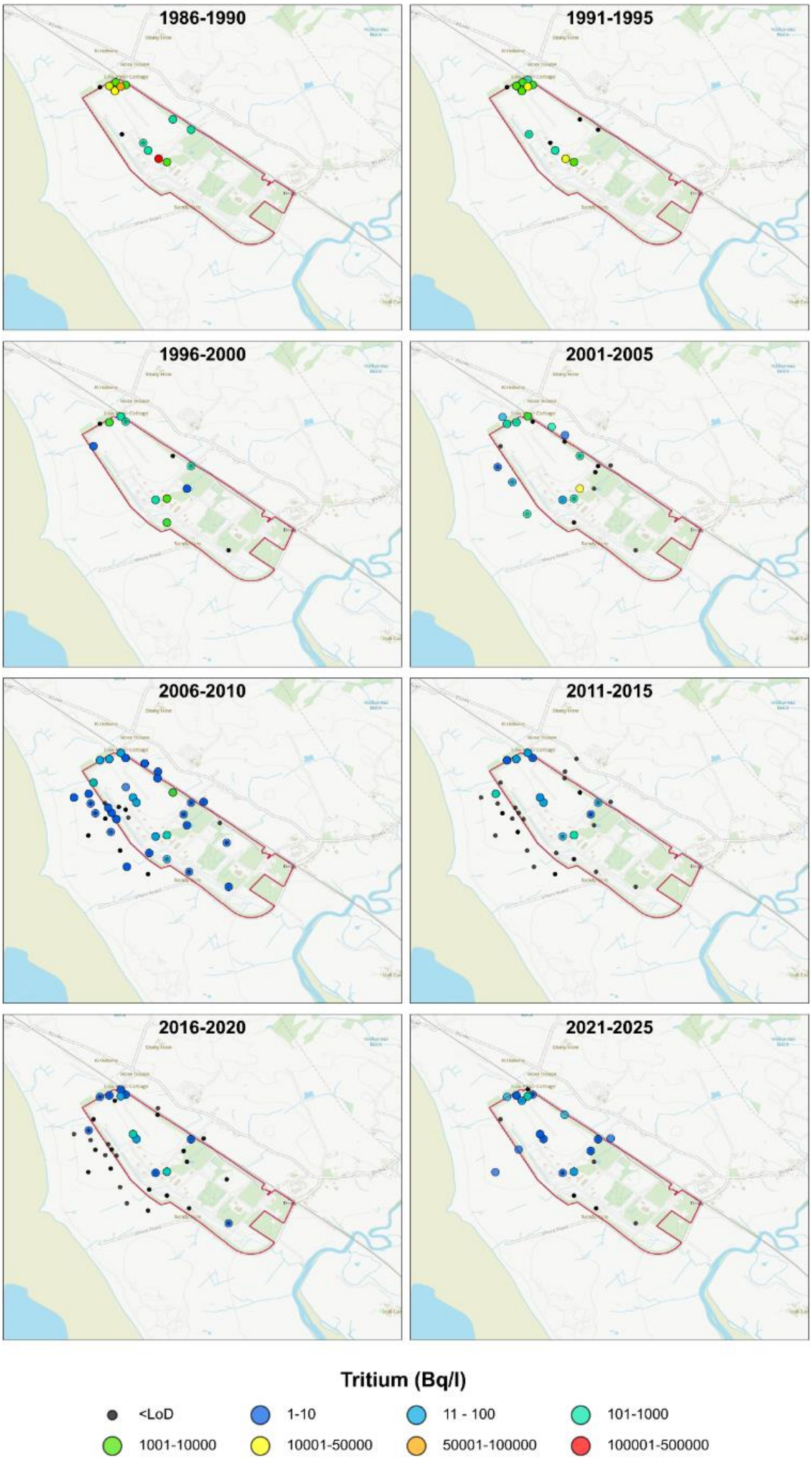


Figure 4.9: Maximum tritium concentrations in Upper Groundwater 2008 to 2025

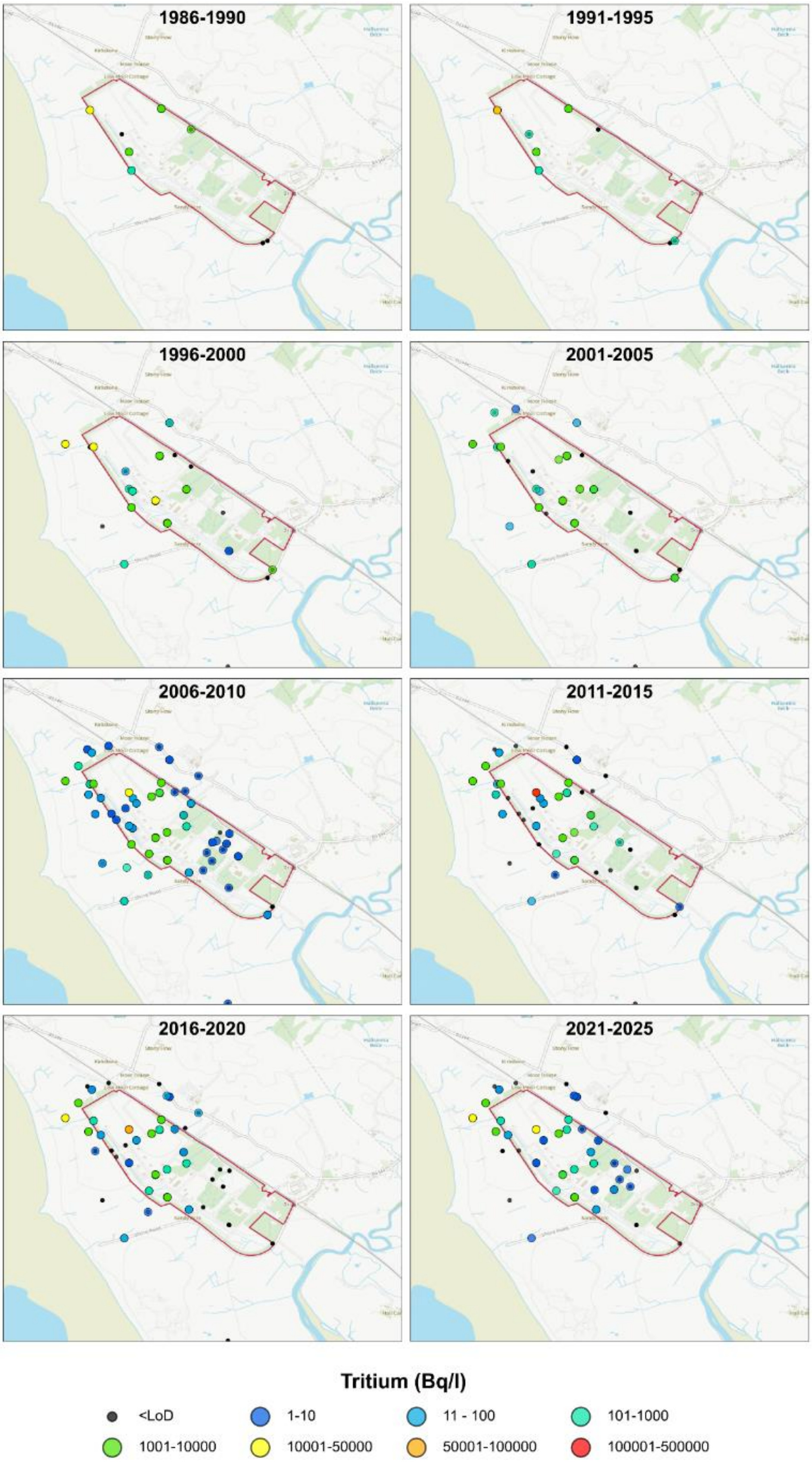


Figure 4.10: Maximum tritium activity within the Medium Regional Groundwater 2008 to 2025

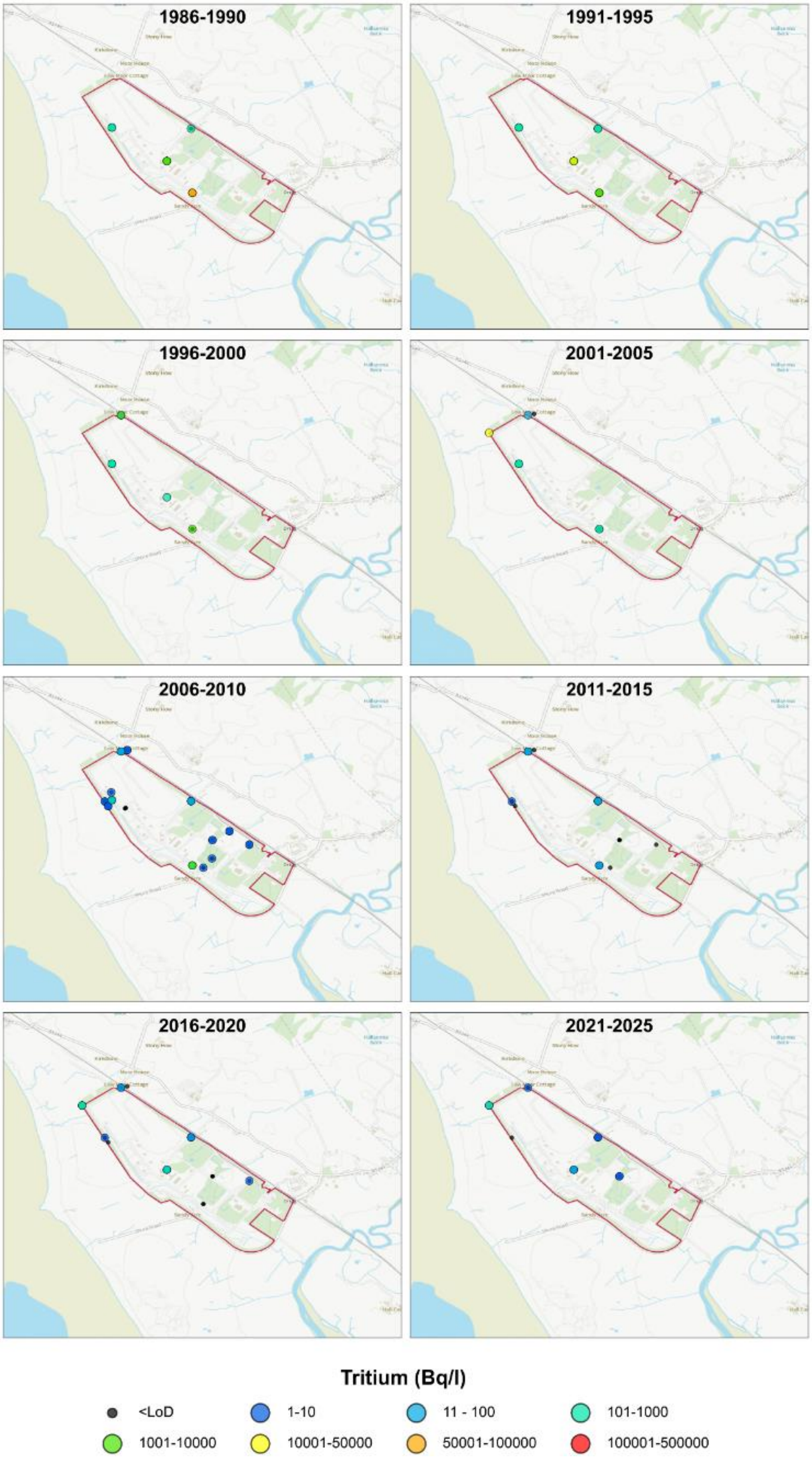


Figure 4.11: Maximum tritium activity within the Intermediate Regional Groundwater 2008 to 2025

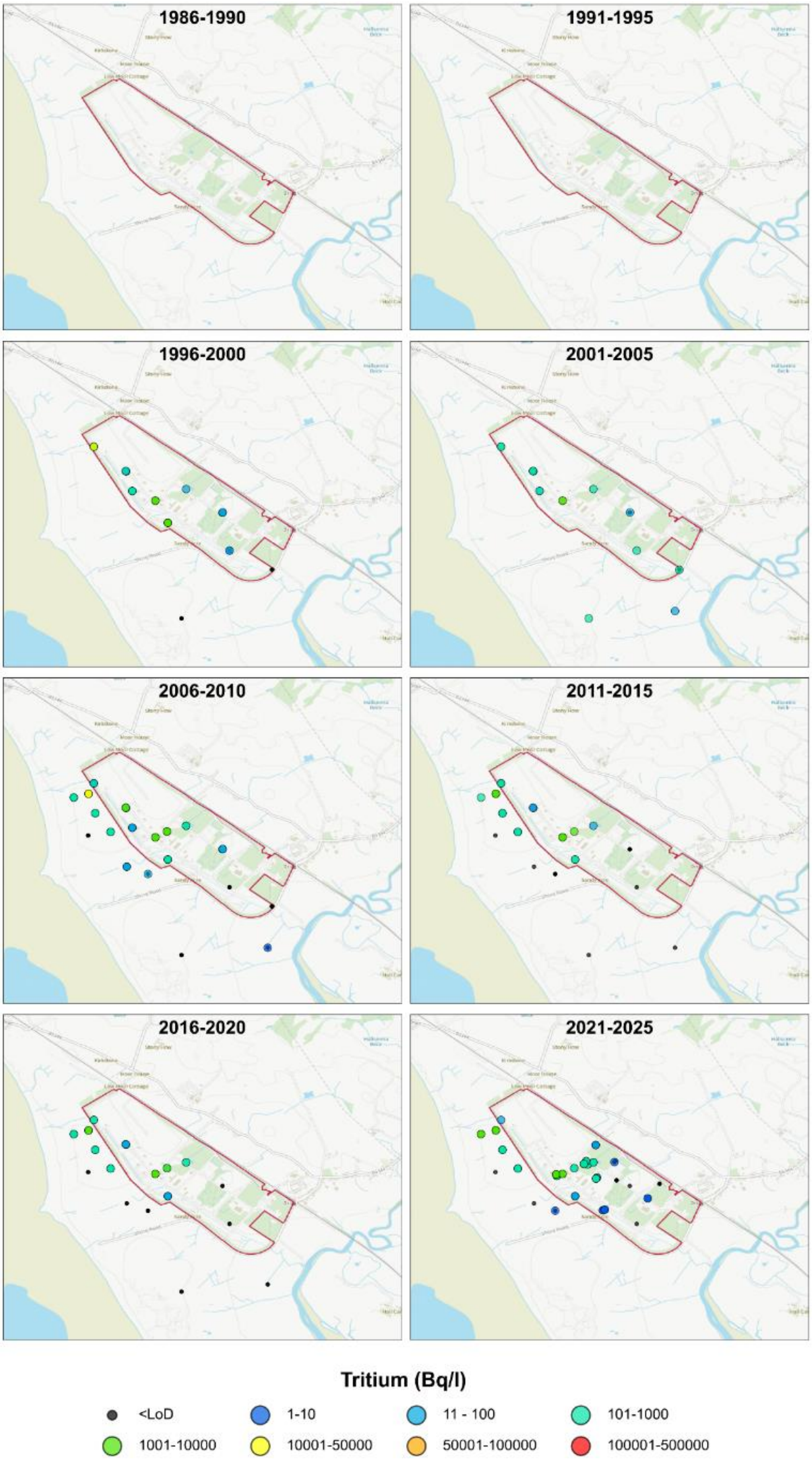


Figure 4.12: Maximum tritium activity within the Deep Groundwater 2008 to 2025

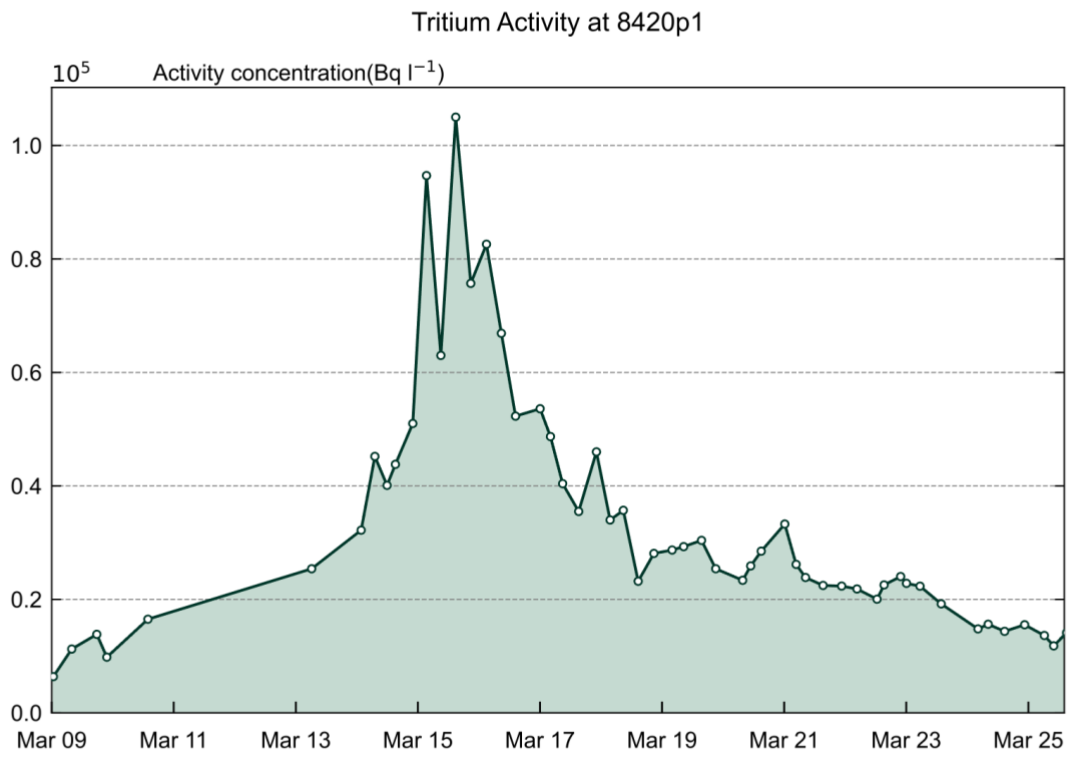


Figure 4.13: Tritium activity at 8420p1

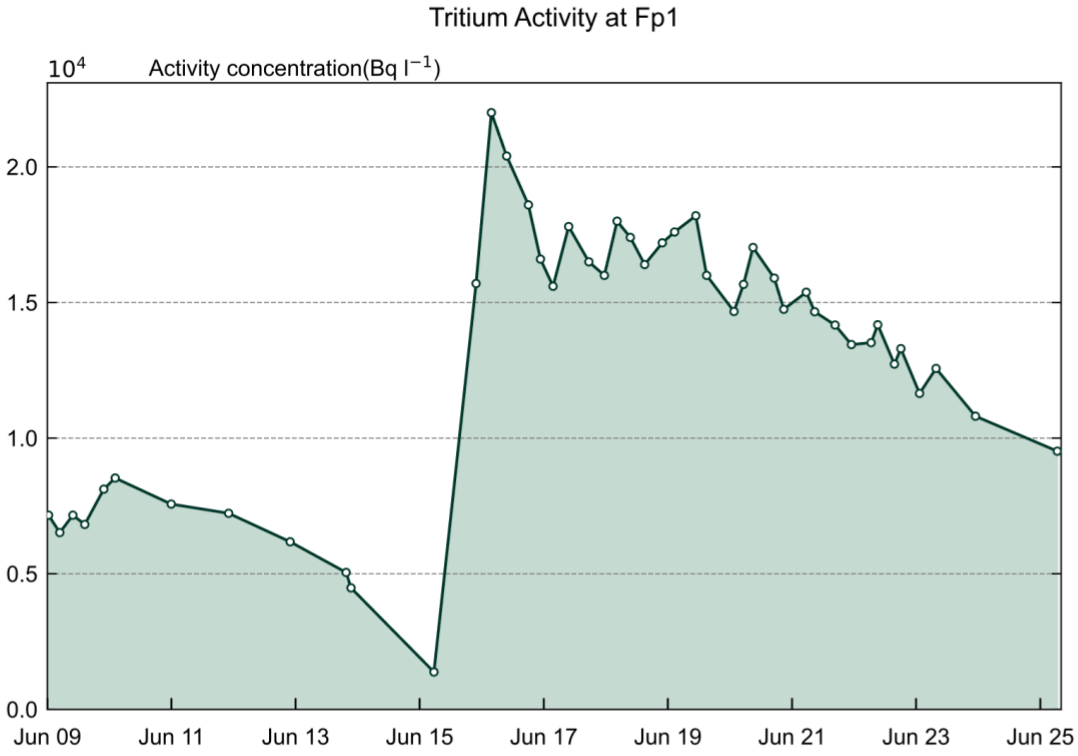


Figure 4.14: Tritium activity at Fp1

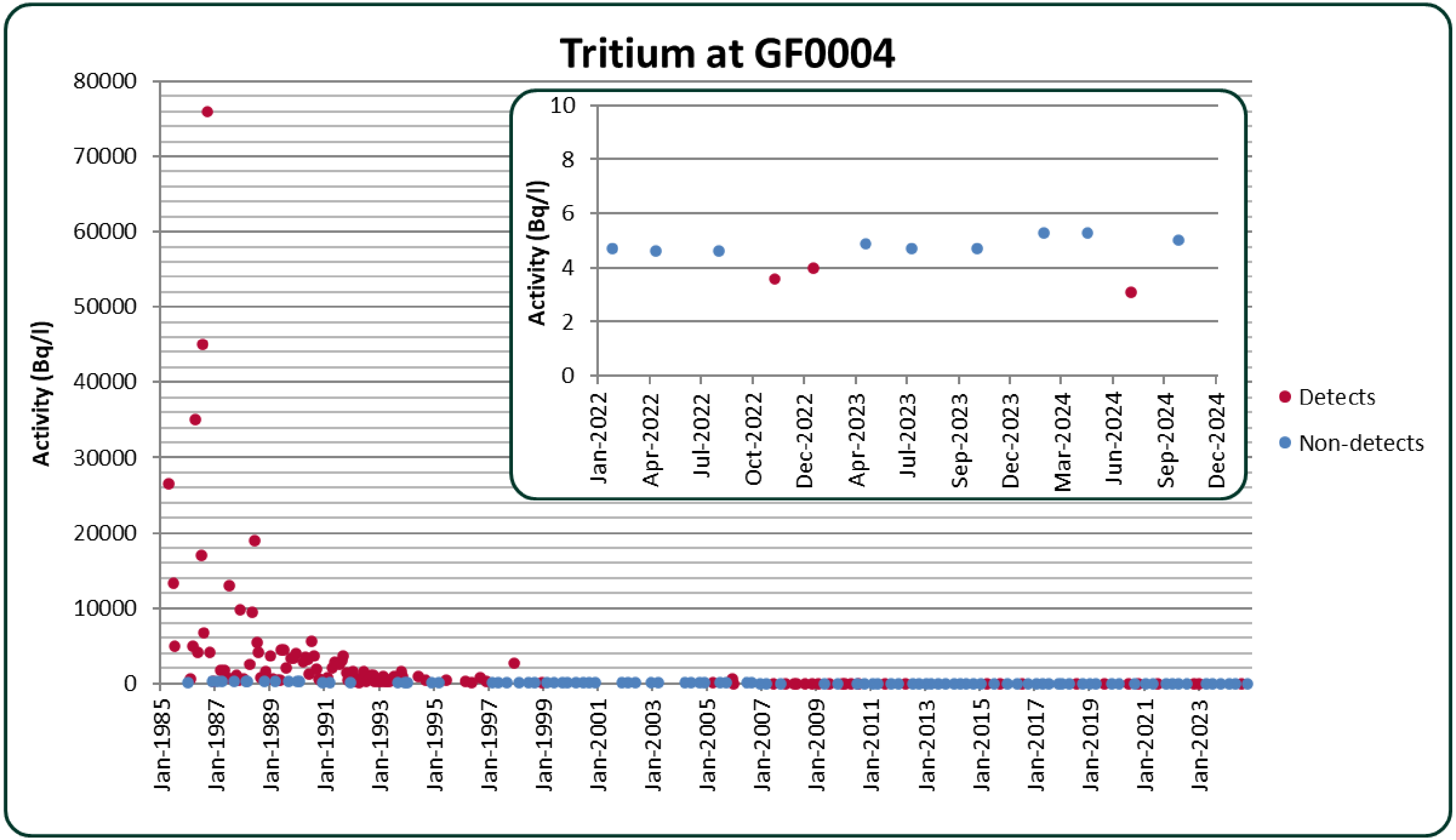


Figure 4.15: Tritium at the GF0004 monitoring point

4.2 Hydrogeological Conceptual Model

The hydrogeological conceptual model links together information from hydrogeological data collected around the site, the understanding of the key characteristics of the groundwater flow, and the geological understanding of the site (described in Section 3). This is described in the hydrogeological conceptual model report [23] and summarised here.

Groundwater flow in the region of interest is mainly in the Quaternary deposits and the upper part of the bedrock. There is groundwater flow in the deeper bedrock, but this is considerably weaker.

Over the region, the water table is generally close to the ground surface (within a few metres). The vertical hydraulic conductivity of the upper Quaternary deposits is generally low so that a significant vertical gradient develops. This allows the rainfall recharge to enter the ground and for water to flow down through the Quaternary deposits. The horizontal hydraulic conductivity of the Quaternary deposits and underlying bedrock is sufficiently low that recharge cannot readily flow away laterally. Instead, water builds up until the lateral head gradients are high enough for the resulting flow to take away the recharge. This is particularly true the near-surface deposits (where the horizontal hydraulic conductivity is particularly low). The water level may build up to the level of local topographic lows, leading to discharge to streams at these locations. There may also be interflow in the unsaturated region above the water table, with discharge to streams and rivers. In places where the level of a stream or river is above the local water table, there may be recharge of groundwater from the stream or river. Flow is generally down through the upper part of the Quaternary deposits and laterally through the bedrock and possibly the lower part of the Quaternary deposits, with possible local upwards flow and discharge to streams or rivers in places. The lateral flow is generally from the higher ground inland towards the coast where the water table is near the sea level.

4.2.1 Hydrogeological Units

The geological conceptual model describes the Quaternary deposits using an event-based stratigraphy. This describes the geological history of the deposits and provides suggestions of their connectivity, even in areas where there are few data. To provide a suitable basis for hydrogeological interpretation however, the geological structure must be reinterpreted in terms of the hydrogeological properties of materials. The 3-D geological model is used as a tool to aid further geological understanding and communication of the current state of knowledge. One key aspect of this is to support the hydrogeological understanding and modelling. The geological units defined within the 3-D geological model are used to define hydrogeological units, considering the extents and lithological descriptions of the units (see Subsection 3.1). This includes considering hydrogeological parameterisation for the units. The heterogeneity of the geological units means that there is a large range in potential bulk permeability within individual units which is typically spanning several orders of magnitude. Consequently, it is difficult to define explicit hydraulic conductivities for each unit. Instead, a range of hydraulic conductivities is assigned for each unit, based on the typical lithological descriptions of the units and measured results from laboratory and in-situ pump tests. These ranges were reviewed and refined with consideration of the test results, observed variability in lithological properties, and predicted variability from conceptual understanding.

A description of each hydrogeological unit is given below and the relationship between the hydrogeological units and the geological units is shown in Table 4.3. The naming convention for the hydrogeological units defined in the 2011 ESC was used where the units in the current conceptual model were deemed hydrogeologically similar to those in the model for the 2011 ESC [98].

Hydrogeological unit A

This comprises all the post-glacial deposits across the region including made ground. These deposits are formed of a wide range of materials including scree on hill slopes, peat, alluvium, alluvial fan and river terrace deposits, lacustrine deposits, blown sand, estuarine and beach deposits, and marine sands and muds offshore. These different materials have widely varying hydrogeological properties, but are treated as a single hydrogeological unit.

Hydrogeological unit B1

This consists of offshore Holocene and glacio-marine deposits, primarily bedded muds, silts, sands and minor gravels, which are partly underlain by terrestrial glacial deposits. These formed in a predominantly marine environment and are of generally low hydraulic conductivity. Due to a lack of data, these deposits are treated as a single hydrogeological unit. B1 is the offshore lateral equivalent of unit A described above.

Glaciofluvial

This is a variable granular unit which is distributed near or at surface on the coastal lowlands to the north of the LLWR.

Hydrogeological unit B2

This comprises a sequence of clays, and sands and gravels, and has been formed in an ice-dammed lake environment. There is a high degree of uncertainty in the distribution and connectivity of the individual layers. They are therefore treated as a single anisotropic hydrogeological unit.

Hydrogeological unit B3

Unit B3 mainly consists of highly permeable sand and gravel outwash deposits. It is subdivided into three units (B3T, B3U and B3L), grouping deposits with similar lithologies. B3L is the thickest hydrogeological unit and acts as a regional aquifer. The B3L unit has been associated with a glacial outwash plain − a notably heterogeneous depositional environment composed of braided river channels leading to a complex distribution of sands and gravels. B3L becomes thinner towards the coast where it is replaced by B3SS.

Hydrogeological unit B3SS

Unit B3SS is similar to B3 but consists of finer grained sands and silts. This leads it to have a slightly lower permeability than unit B3, but it still forms part of the regional aquifer. As with unit B3, it is subdivided into three units.

Inland Lake

This consists of glacio-lacustrine deposits of cohesive silts, sands and clays. It represents deposits from historical lakes to the east of the LLWR site and positioned between the margins of the Wasdale and Eskdale valleys as well as more recent lakes from the Scottish Readvance.

Outwash and till

Variable unit dominated by sands and gravels with diamicton.

Hydrogeological unit C

This is a low permeability deeper deposit that consists of cohesive silts and clays (CU) and homogenous till units with variable gravel and sand units (CL). CL differs from the outwash and till unit as it is lower permeability.

Hydrogeological unit D

This comprises all the older deposits at depth. It consists of a mixture of clays, silts, sands and gravels. It is subdivided into:

- D1, which comprises sands and gravels;
- D2, which comprises coastal muds (clays and silts);
- D3, which comprises gravels;
- D4, which comprises coastal muds (clays and silts).

Bedrock units

The bedrock is split into six units based on the bedrock subdivisions discussed in Section 3. The Helsby Sandstone lies directly beneath the Quaternary deposits on site, which in turn is underlain by the Wilmslow Sandstone.

Table 4.3: Hydrogeological units in the hydrogeological conceptual model

Stratigraphic unit	Hydrogeological unit
Made Ground	A
Holocene Marine/Beach Sands	
Upper Alluvium	
Dune	

Stratigraphic unit	Hydrogeological unit
Peat/ Organic Clay	
Lower Alluvium	
Holocene Marine Silts and Muds	B1
Post-Scottish Readvance Glaciomarine sands, clays, and silts	B1
Ice Dammed Lake [Channel]	B3T
Scottish Readvance Inland Lake	Inland lake U
Scottish Readvance Glaciofluvial units	Glaciofluvial
Ice Dammed Lake	B2
Scottish Readvance Till and Outwash	Outwash till U
Pre-Scottish Readvance Outwash	B3U
Post-LGM Sands	B3SSU
Post-LGM Infilled Channels	CU
LGM Inland Lake	Inland lake L
LGM Outwash	B3L
LGM Till and Outwash	CL
Pre-LGM Alluvial Sands and Silts	B3SSL
Pre-LGM Coastal Muds 2	D4
Pre-LGM Marine Sands	B3SSB
Pre-LGM Estuarine Gravel Bed	D3
Pre-LGM Coastal Muds 1	D2
Pre-LGM Till and Outwash	Outwash till L
Pre-LGM Outwash	D1

Stratigraphic unit	Hydrogeological unit
Mercia Mudstone	Mudstone
Sherwood Sandstone Group - Helsby Fm	Helsby Sandstone
Sherwood Sandstone Group - Wilmslow Fm	Wilmslow Sandstone
Sherwood Sandstone Group - St Bees Fm	St Bees
Borrowdale Volcanic Group	BVG
Lake District Felsic Pluton	Granite

4.2.2 Description of Conceptual Model

The Upper Groundwater sits in the top layer of Quaternary deposits, above the Regional Groundwater and below the surface and soil zone. It is marked by a strong vertical gradient in groundwater heads (see Figure 4.7), which causes water to flow downward toward the Regional Groundwater. This vertical gradient, caused by low vertical hydraulic conductivity in hydrogeological unit B2 near the LLWR, sets the Upper Groundwater apart from the Regional Groundwater. The distinction between Upper and Regional Groundwater aligns with the difference between hydrogeological units B2 and B3, as shown in Figure 4.16.

Figure 4.17 schematically illustrates this: Upper Groundwater generally flows downward (with some horizontal movement), while discharge areas, often near streams, show upward flow. Regional groundwater flows horizontally and discharges into the sea, with localised outflows to nearby streams (such as the Drigg Stream and East-West Stream, see Figure 4.2) and other areas south and east of LLWR, sometimes linked to field drains. Overall groundwater flow follows the previously described head gradients.

Regional Groundwater is found in deeper Quaternary deposits and bedrock, distinguished from Upper Groundwater by different hydraulic head gradients. While Regional Groundwater shows minimal vertical but weak horizontal gradients (generally perpendicular to the coastline), flow moves roughly northeast to southwest. Where sandstone forms the upper bedrock, it notably contributes to Regional Groundwater flow. This Regional Groundwater flow zone includes hydrogeological unit B3 and underlying Quaternary units as well as the bedrock. Although distinct, Upper and Regional Groundwater are interconnected with flow between them.

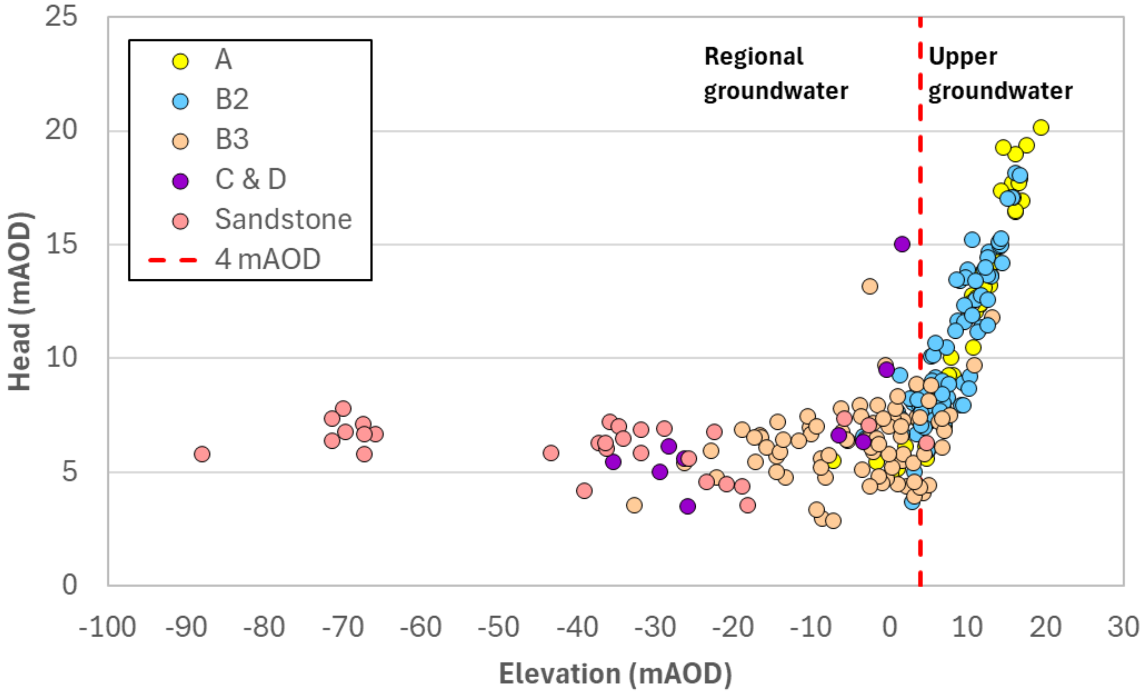


Figure 4.16: The observed heads in the boreholes near the LLWR plotted against the elevation of the centre of the screened interval. The figure also shows the point 4 m above OD elevation, which is the approximate boundary between the Regional and Upper Groundwaters and is approximately at the level of the interface between the B2 and B3 units. The points are coloured according to the hydrogeological units [23].

Particle paths from the LLWR are projected to move downward through hydrogeological unit B2 into the Regional Groundwater (mainly B3 and B3SS), then travel almost horizontally until discharging in the inter-tidal region [24]. Due to the low vertical hydraulic conductivity of B2 and the higher horizontal conductivities of the Regional Groundwater, only a small downward flow is expected, keeping paths near the top of the Regional Groundwater. The most permeable regional units are B3 and B3SS (shown as one in Figure 4.17).

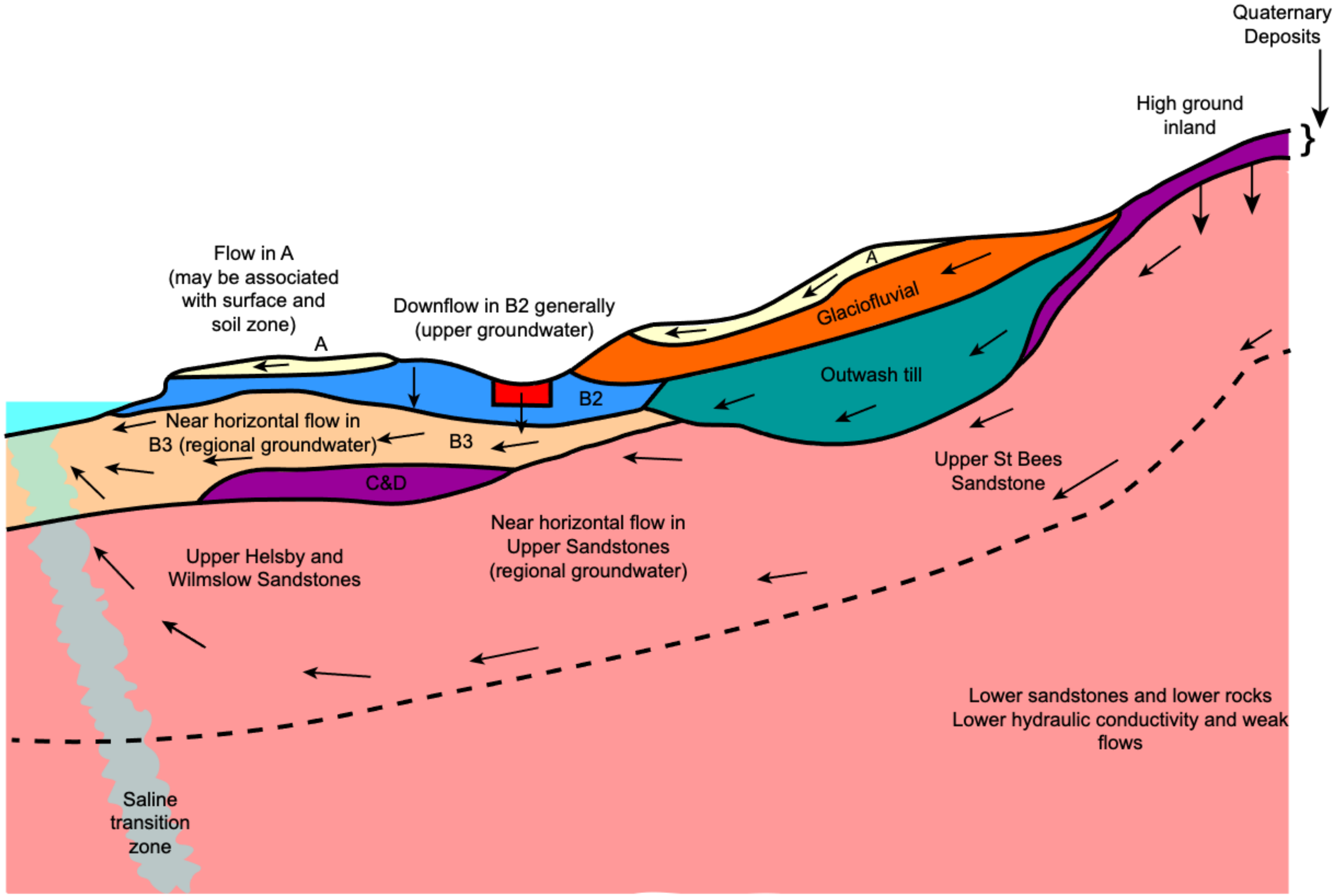


Figure 4.17: Schematic picture of the flow in a vertical section through the LLWR perpendicular to the coast. The arrows show only the direction of the flow, not its magnitude. Some units, such as B3 and B3SS, are combined for simplicity [23].

4.2.3 Effects of Engineering and Site Evolution

The excavation of trenches, Vault 8 and Vault 9, has resulted in localised depressions in the topography, potentially providing sites for Upper Groundwater discharge during open excavation periods and causing localised lowering of the water table. Groundwater flow patterns may also be locally influenced by the presence of filled vaults and trenches.

The interim cap over the trenches was installed in 1989 and extended in 1995. It has substantially reduced recharge by redirecting water to associated drainage systems. As a result, the water table beneath the interim cap is lower than would be expected under natural conditions, resulting in an unsaturated zone extending to greater depths.

Furthermore, the cut-off wall, constructed between 1989 and 1995, has significantly decreased horizontal groundwater flows to the railway drain demonstrated by the decrease in tritium levels. Plans are in place to extend this cut-off wall to the south and west, ultimately enclosing the entire LLWR. This extension is anticipated to further restrict horizontal groundwater movement within the bounded area.

Construction of the future vaults will create local depressions in topography and influence groundwater nearby. The bases and walls, initially made with low permeability bentonite-enriched sand and concrete, will limit water flow. Before closure, any water entering the vaults will be drained, keeping water levels low and the contents mostly unsaturated.

The final cap will be installed in phases and is expected to greatly reduce groundwater recharge beneath it at first with minimal infiltration into the waste. While the cap may degrade over time, increasing infiltration and raising water levels, studies indicate it should remain effective for up to 2,000 years [99].

After waste disposal, the ISO freight containers are expected to remain mostly intact until the coastline crosses the site. Figure 4.18 illustrates the expected evolution of the flows through the vaults over time. More details on the expected changes are given in the '*Near Field*' report [6]. Following closure, the majority of water descending from the cap will initially be consumed by corrosion. Even if partially corroded, the containers should still act as barriers, causing water to flow mainly through the gaps between them (see Figure 4.18a). When fully intact, these containers prevent water from contacting the waste, so no contaminants migrate; however, the groundwater assessment conservatively assumes that they offer no such barrier [13, 14]. Over time, corrosion will allow some water to pass through the containers and contact the waste, though most water will continue to flow through the gaps.

Over time, this may result in water accumulation and the formation of a saturated zone at the base of the vaults as shown in Figure 4.18b. Due to low infiltration rates, the extent of this saturated region is expected to remain minimal during the period of interest (5000 years post capping). Once active leachate management ends, infiltration is assumed to remain low but water levels within the vaults may rise to the top of the vault walls. If so, water could overflow from Vault 9 and the future vaults into the drainage blanket, subsequently flowing beneath the vaults into the underlying geology (see Figure 4.18c).

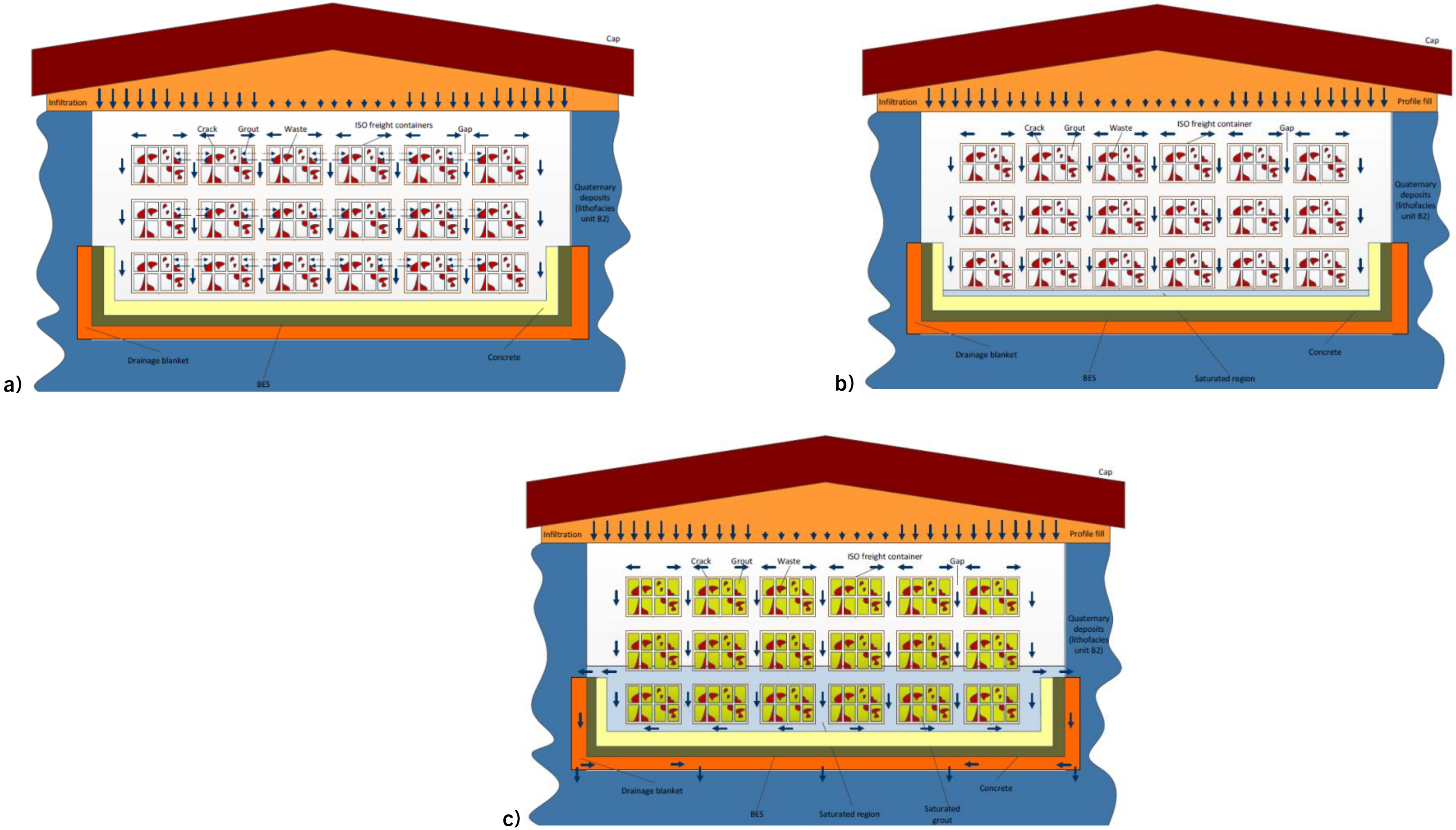


Figure 4.18: Schematic illustration of water flow in a vault at a) early times, b) after container failure and c) at later times. Figures are not to scale and the rectangular pattern of cracks in the grouted waste is for clarity only. Reproduced from reference [100].

The timing of this occurrence depends on changes in infiltration rates, governed by the evolution of the final cap, as well as the porosity of vault materials and the degradation of the bases over time, which would permit increased flow. Given the anticipated low infiltration, it is considered unlikely that this process will occur before the coastline reaches the site and that the majority of the waste will remain unsaturated.

The water levels in the trenches are expected to remain low with the construction of the final cap. As the cap degrades, water levels in trenches will rise, and drainage via trench bases will become the main route for leachate migration.

Over time, global climate change is expected to lead to loss of part, or all, of the polar ice caps, leading to sea-level rise due to meltwater from the ice caps. As a result, the sea-level will rise near the LLWR. There is large uncertainty about the magnitude and timing of sea-level rise, and three climate scenarios have therefore been adopted. Under the reference climate case sea-level rise is about 6 m, and under the high-emissions scenario the sea-level rise is about 12 m [7]. Global climate change is expected to lead to a pattern of warmer, wetter winters and drier summers, compared with present-day at the LLWR.

Currently, the closest point of the LLWR vaults lies approximately 350 m inland from the present-day coastline, which is gradually receding. With sea levels projected to rise in the future, the rate of coastal recession will increase. It is almost certain that the repository will be disrupted due to coastal erosion. Based on the current understanding of the coastal system and quantitative modelling studies, it is concluded that the disposal vaults will begin to be eroded on a timescale of several hundred to a few thousand years.

Sea-level rise and coastal erosion are not expected to change the broad features of the flow described above. As a result of sea-level rise, the head in the Regional Groundwater may rise (dependent on the accompanying climate conditions). The head drop across the Upper Groundwater may therefore reduce, leading to a reduction of vertical flow through the Upper Groundwater.

For longer time periods, it remains unlikely that the LLWR would be disrupted by estuary processes irrespective of sea level and sediment supply. This is based on an updated assessment of geomorphological behaviour of the Irt Estuary including the main potential erosion risks to the repository. This has been considered for the 2026 ESC in response to revised projections of sea-level rise and shoreline retreat. While timescales for coastal erosion have also been revised, repository disruption will still occur through coastal erosion before estuary process can have an impact. The estuary could only eventually affect the southern part of the site (but not the repository) through flooding, if coastal erosion is much slower than anticipated under any emissions scenarios. The potential effects of future evolution of the site on the groundwater chemistry were reviewed, including the effects of climate change, sea-level rise and coastal erosion. This indicated that a number of processes are likely to lead to an increase in salinity of the groundwater, but that it is only likely to become saline once coastal erosion has progressed close to the LLWR facility or sea-level rise has reduced the hydraulic head to much lower levels. The viability of the groundwater as a pathway is significantly reduced in this situation. The assessment of the groundwater pathway ceases when coastal erosion of the LLWR commences.

4.3 Water Resources

Groundwater is considered to be a potential resource. In the recent past, extraction of resources in the vicinity of the site is limited to small-scale water abstraction, primarily for agricultural purposes [42] and in the nineteenth century, use of spring water for medicinal purposes [101]. Groundwater in the Permo-Triassic sandstones in West Cumbria is classified as being a Principal Aquifer [102] of overall good quality [103]. Groundwaters in the Quaternary deposits are classed as Secondary Aquifers (typically sands and gravels - B3) or Secondary undifferentiated aquifers (mixed deposits - B2).

A water features survey carried out in 2023 [104], combined with information on private water supplies in the area was provided by Cumberland Council [105], indicates that there were no private water supplies and licensed abstractions in the vicinity of the site, as shown in Figure 4.19, and that the site does not lie within a source protection zone. Wells in the region tend to target the sandstone as the source [106]. It is considered unlikely that a borehole would be terminated in the sands and gravels of lithofacies unit B3 to provide water for human consumption but that shallower wells may use the near-surface Quaternary deposits to provide water for animal watering [107].

A water abstraction licence [NW/074/0007/012] has recently been granted, from 6th January 2025 until 31st March 2038, to allow the use of one of the on-site boreholes to supply water from the Principal Aquifer for dust suppression as part of cap construction works. The abstraction is expected to only operate intermittently in dry periods with a maximum abstraction rate of 493 m^3 day^{-1} and is not expected to have a significant impact on groundwater flow [108]. This borehole will be decommissioned before site closure.

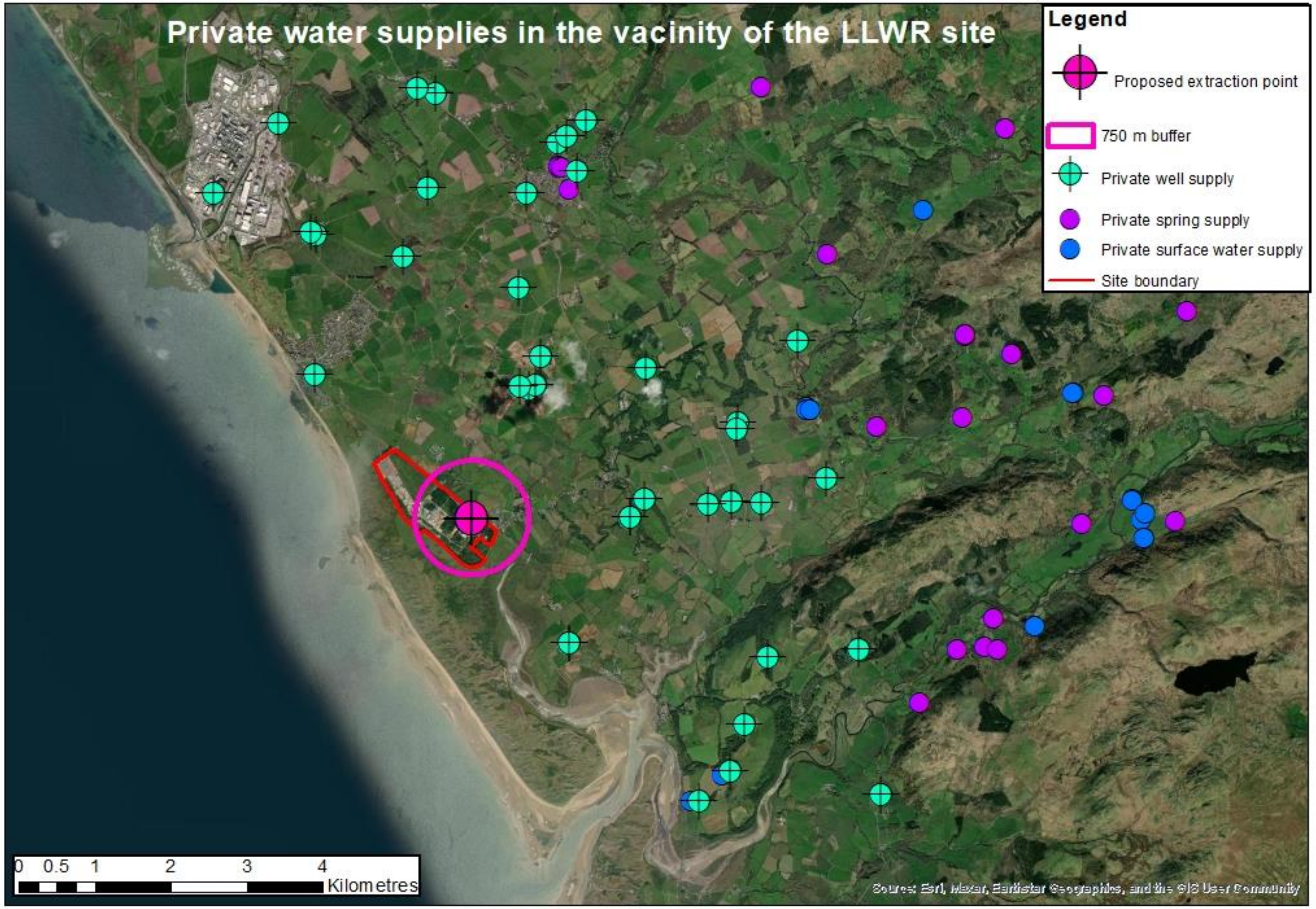


Figure 4.19: Private water supplies in the vicinity of the LLWR site

5 Hydrogeological Modelling

5.1 Modelling Approach

Hydrogeological models were developed to represent the movement of groundwater. The models can involve simple 1-D calculations or more complex 3-D representations. Our approach has been to use a combination of models to first represent the hydrogeological conceptual model in detail and then a simplified groundwater flow model that can be used to represent that understanding within the assessment model. We have calibrated the more detailed groundwater flow model against observed heads and other observations. The calibrated model provides an acceptable match to a range of observations, which builds confidence. We have developed versions of the detailed model to represent changes in coastal erosion, changes in climate, and changes in the performance of the engineered materials over time. A detailed review of hydrogeological model development, calibration and calculated results is presented in reference [24].

The development of the LLWR hydrogeological models has followed a structured approach, consisting of a series of steps, as illustrated by Figure 5.1. This approach is intended to build a robust, quantitative understanding of the movement of groundwater near the LLWR. As with the geology, the hydrogeological models have continued to be developed since the 2011 ESC [75] to ensure that they encompass the latest understanding. This included an updated hydrogeological assessment model [109] to support the HRA submission in 2017 [95].

Two hydrogeological models are used to support the LLWR ESC:

- A regional-scale finite-element groundwater flow model. This is a detailed model of the area around the site, developed using the ConnectFlow finite-element software [110]. This integrates the geological model with understanding of the site hydrogeology and is calibrated against a range of different information sources including groundwater levels from boreholes, trench probes, stream flow gauges, trench leachate flows, and transient fluctuations in water levels. The hydrogeological model is implemented on two levels: a large-scale regional model; and a site-scale model, which includes a representation of the repository engineering for the purpose of modelling groundwater flows in and around the repository. This model aids understanding of the hydrogeology in the region as well as providing key inputs to the groundwater assessment model.
- A local scale compartment flow model (CFM). This is simplified model of the hydrogeology which has a smaller domain than the finite-element model, extending vertically from the repository down to the B2 geological layer and laterally to a small distance outside of the cut-off wall. It was constructed as a system of inter-linked compartments, each representing a particular vault, part of a trench or part of the

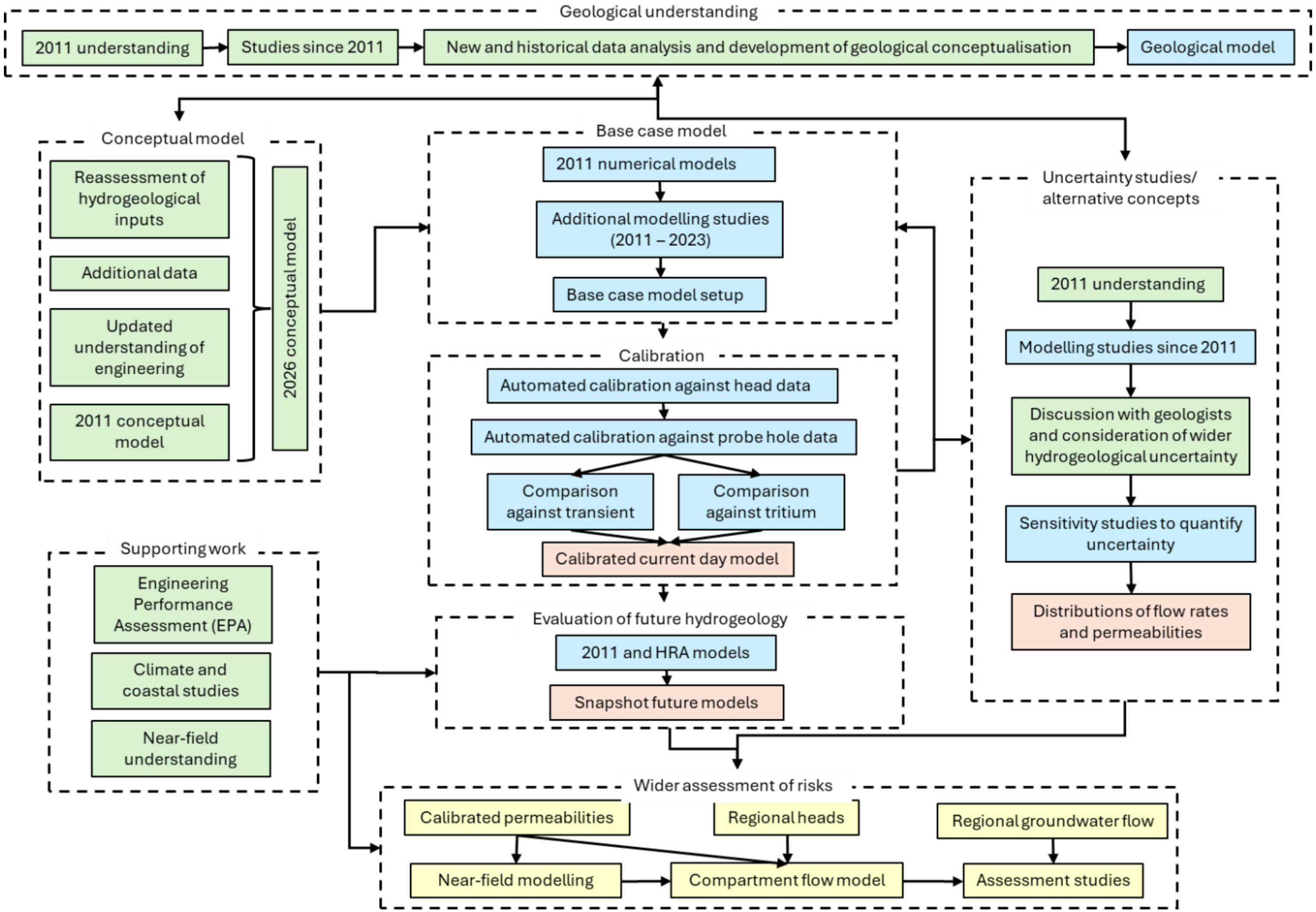


Figure 5.1: **Flow diagram illustrating the development of the hydrogeological models. Green boxes indicate inputs (data, conceptual models), blue boxes indicate modelling tasks, orange boxes indicate key outputs (conclusions or interpretations), and yellow boxes indicate input to the assessment modelling [24].**

surrounding or underlying geology. The primary outputs are the evolution of water levels in each compartment and the flows between pairs of compartments. The objectives were to represent the continuous evolution of the system and to have the ability to evaluate the consequences of uncertainties in the hydraulic properties of the engineered components and geology using a probabilistic approach. The CFM uses significantly less computational resources per simulation than the 3-D groundwater flow models. This makes it feasible to carry out calculations for hundreds of realisations, as required when undertaking probabilistic cases. The equivalence between the CFM and assessment model compartments allows the CFM to be embedded directly within the assessment model.

The set of steps outlined below were used to develop the regional-scale ConnectFlow model for the 2026 ESC as reported in [24]:

1) Develop a conceptual model of the groundwater flow and transport at LLWR; this model is underpinned by the geological description of Quaternary deposits and bedrock together with interpretations of the site monitoring data.
2) Construct a ConnectFlow numerical model of the current-day groundwater flow and transport at LLWR and its environs using surfaces from the 3-D geological model. This is referred to as the Current Day Model because it represents the present hydrogeological conditions at the LLWR site, rather than future or hypothetical states. It is the reference point for calibrating the ConnectFlow model and the CFM before projecting into future scenarios.
3) Calibrate the ConnectFlow model. The calibration uses observed groundwater head measurements at boreholes both on and off the LLWR site. The purpose of the calibrated model is to reproduce observed hydrogeological conditions.
4) Use the ConnectFlow model to compare with independent measures, such as transient fluctuations in water levels and water quality observations, as confidence building exercises.
5) Conduct uncertainty studies to quantify the potential impact of uncertainties on key inputs to the groundwater assessment model.
6) Use the current day groundwater flow model to construct ConnectFlow models at a series of times following closure of the repository, taking into account the construction of new engineered features, climate change, sea-level rise and coastal erosion.

The set of steps outlined below were used to develop the site-scale CFM.

7) Update the CFM to ensure that it is consistent with the latest understanding.
8) Calibrate the CFM against the finite-element model. This includes calibrating the repository water levels in the CFM against those in the ConnectFlow model and by comparing the B3 flow rates to ensure consistency between the two models.

9) Interface with the groundwater assessment model by supplying key inputs to both the groundwater assessment model and the CFM, including regional groundwater flow rates and water levels.

5.2 Current Day 3-D Groundwater Flow Model

5.2.1 Model Description

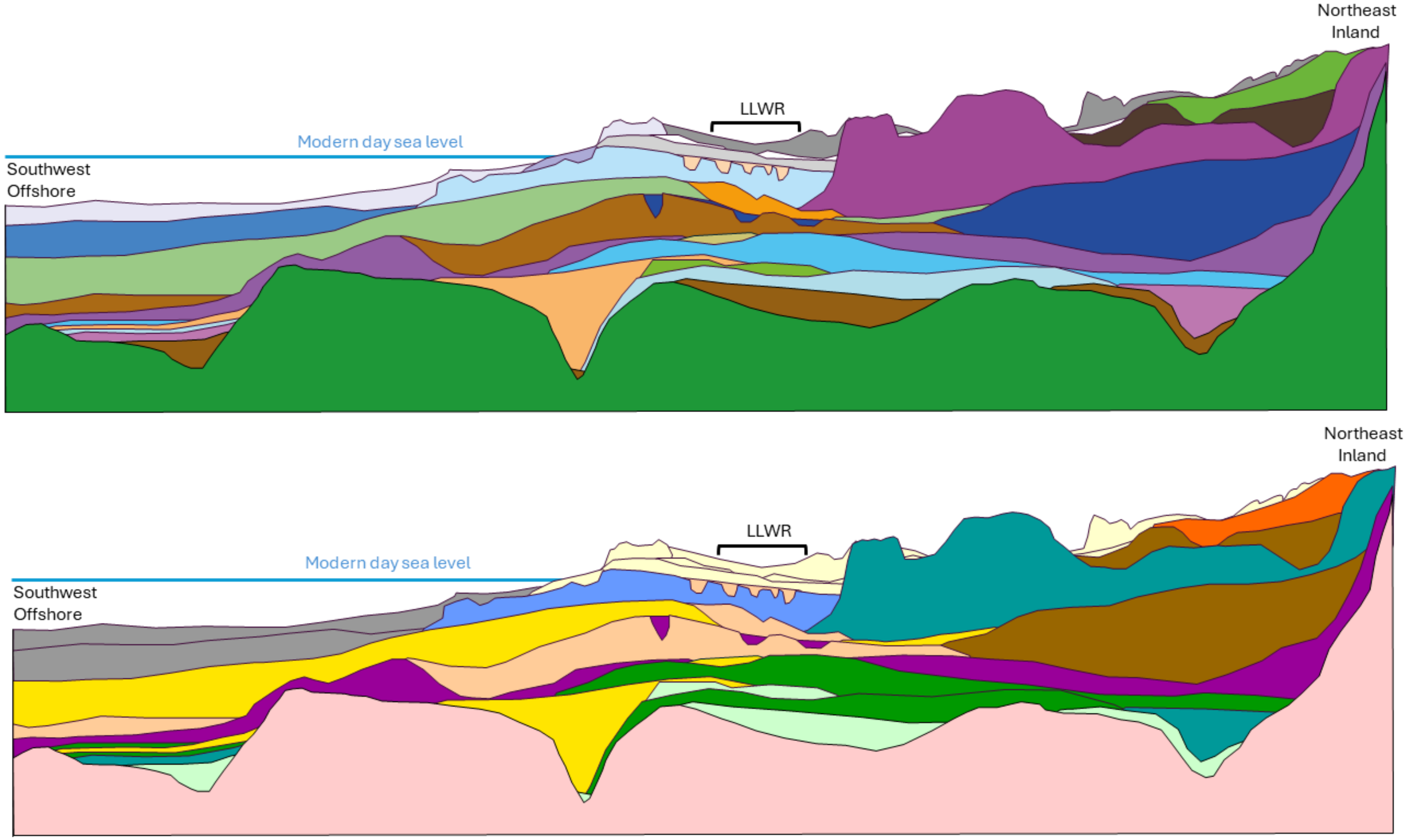
Groundwater flow is modelled using a continuous porous medium model in the hydrogeological modelling software ConnectFlow [110]. ConnectFlow is considered to be an appropriate choice of software because:

- it accurately handles flow through porous matrices − e.g. aquifers, soils, clays − both under transient and steady-state conditions;
- it enables fine-scale representations of the engineered features within regional-scale models, ensuring consistency across model scales;
- it uses the finite-element method which is ideal for complex geological geometries.

As explained above, the hydrogeological model is implemented on two scales (shown in Figure 3.6): a regional-scale and a site-scale. The regional-scale model has boundaries that correspond to locations where topographic and hydrological features suggest physical boundary conditions for the groundwater flow (such as rivers). All onshore regional boundaries are about 5 km from LLWR, and the offshore boundary extends about 3.5 km offshore (where significant lower permeability mudstone deposits are expected). The boundary condition imposed on all lateral boundaries is no-flow.

Surfaces representing the base of each hydrogeological unit are extracted from the geological model in Leapfrog and the hydrogeological model grid is mapped onto these surfaces. Figure 5.2 shows a schematic cross-section of the geological units and the equivalent hydrogeological units

Major faults and fault zones are present in the bedrock, but studies [111] suggest they have little influence on groundwater flow in the Quaternary and upper bedrock, so they are not included in the model. Nirex examined the effects of faulting on sandstone hydrogeology and concluded that any impacts are minor, as affected zones are narrow and have properties similar to the surrounding rock [89]. A later study, which explicitly represented faults, also found they had negligible impact on groundwater pathways from the LLWR [111]. Further work to assess potential effects of faulting through variant cases has also been carried out as part of uncertainty studies (see Subsection 5.3).



Stratigraphic unit	Hydrogeological unit
H-MSS	B1
H-BS	A
H-A2	
H-D	
H-P	
H-A1	
PoSR-GM	B1
IDL-Cl	B3T
SR-IL	Inland lake U
SR-G	Glaciofluvial
IDL	B2
SR-TO	Outwash till U
PrS-O	B3U
PoLGM-S	B3SSU
PoLGM-IC	CU
LGM-IL	Inland lake L
LGM-O	B3L
LGM-TO	CL
Pr-LGM-AS	B3SSL
Pr-LGM-CM2	D4
Pr-LGM-MS	B3SSB
Pr-LGM-EGB	D3
Pr-LGM-CM1	D2
Pr-LGM-TO	Outwash till L
Pr-LGM-O	D1
SSG - Helsby	Helsby Sandstone

Figure 5.2: Schematic cross-section showing the geological units (top) and the equivalent hydrogeological units (bottom) from roughly southwest offshore to northeast inland through the LLWR site. The section is schematic only and does not correspond to a single location. The display of channel features does not reflect their true orientation relative to the section [24].

Hydrogeological properties are assigned to each of the hydrogeological units to represent their compositions. For the engineered materials, hydraulic conductivities were taken from the Engineering Performance Assessment (EPA) [99]. For the hydrogeological units, there is a degree of uncertainty regarding the hydraulic conductivities due to heterogeneity and the sparseness of direct geological measurements. For this reason, a set of prior distributions have been defined for the bulk hydraulic conductivities reflecting the stratigraphy as observed in borehole cores together with understanding of the formation process, see Figure 5.3. These take the form of truncated log-normal distributions, with means and standard deviations reflecting best estimates and uncertainty intervals, together with upper and lower bounds.

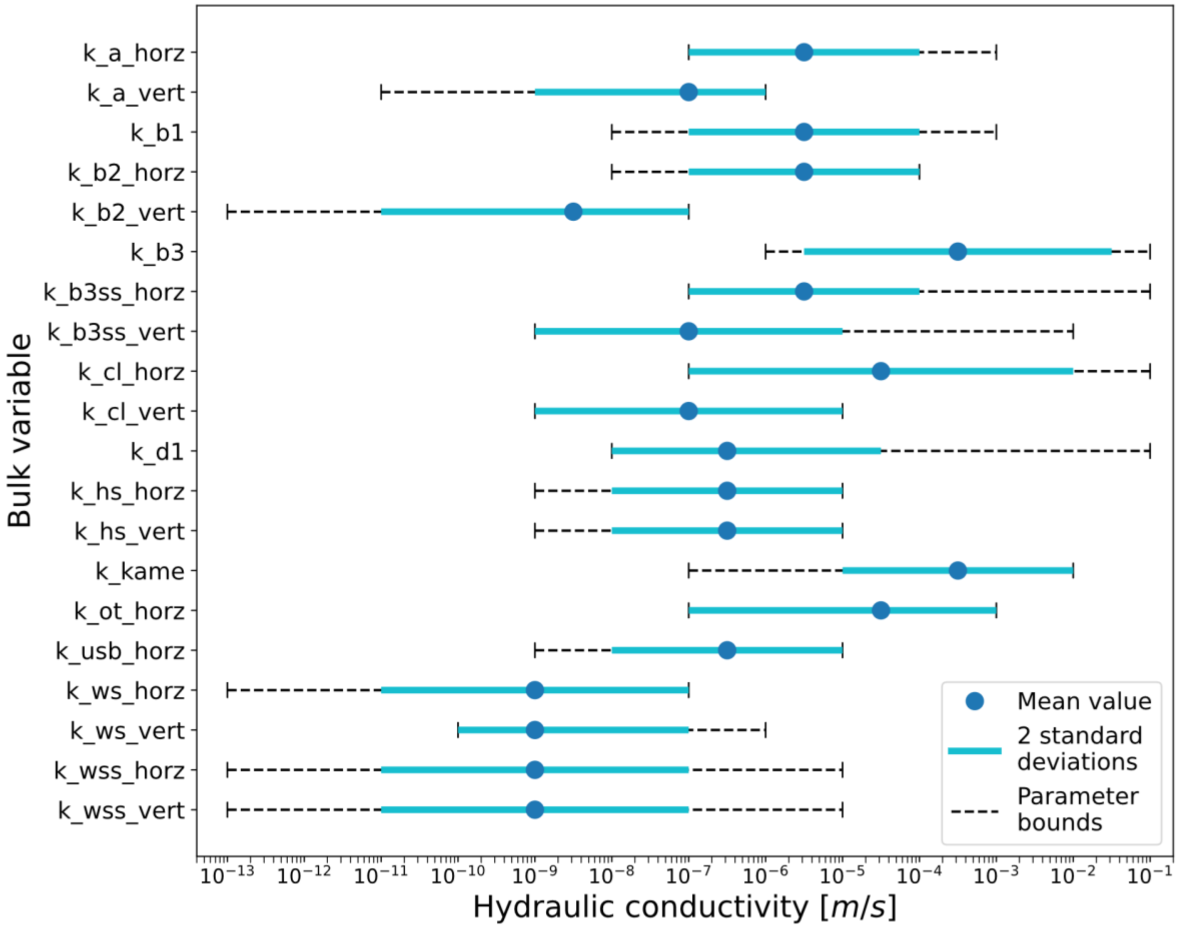


Figure 5.3: Prior distributions for bulk hydraulic conductivities. Truncated log-normal distributions are illustrated by blue dots and intervals for the means and standard deviations, and black dashed intervals for the upper and lower bounds.

The prior uncertainty in each bulk hydraulic conductivity typically spans several orders of magnitude, and as such this is broadly expected to be the most significant source of uncertainty in the LLWR hydrogeological model.

The engineered components (e.g. trenches, vaults, waste, cut-off walls and cap) also need to be represented to enable the calculation of groundwater flow through and around these components. Hence, a highly refined grid representation of the engineered features is included in the site-scale model. The current-day modelling concentrates on the current-day engineering, including Vault 9, which was constructed in December 2010. This was chosen to be consistent with the period in which the groundwater monitoring data was acquired (2011 to 2021).

The site-scale model represents explicitly the geometry and hydrogeological properties of engineered components. There are two main exceptions: firstly, the interim trench cap, which is modelled using a reduced infiltration boundary condition rather than explicitly including the geomembrane in the model; secondly, the concrete slab and drainage layer beneath Vault 8, which are modelled using an effective conductivity. Figure 5.4 provides an overview of the engineering represented in the site-scale model. The interim cap and profiling have been removed to show the layout in the trench area and Vault 8.

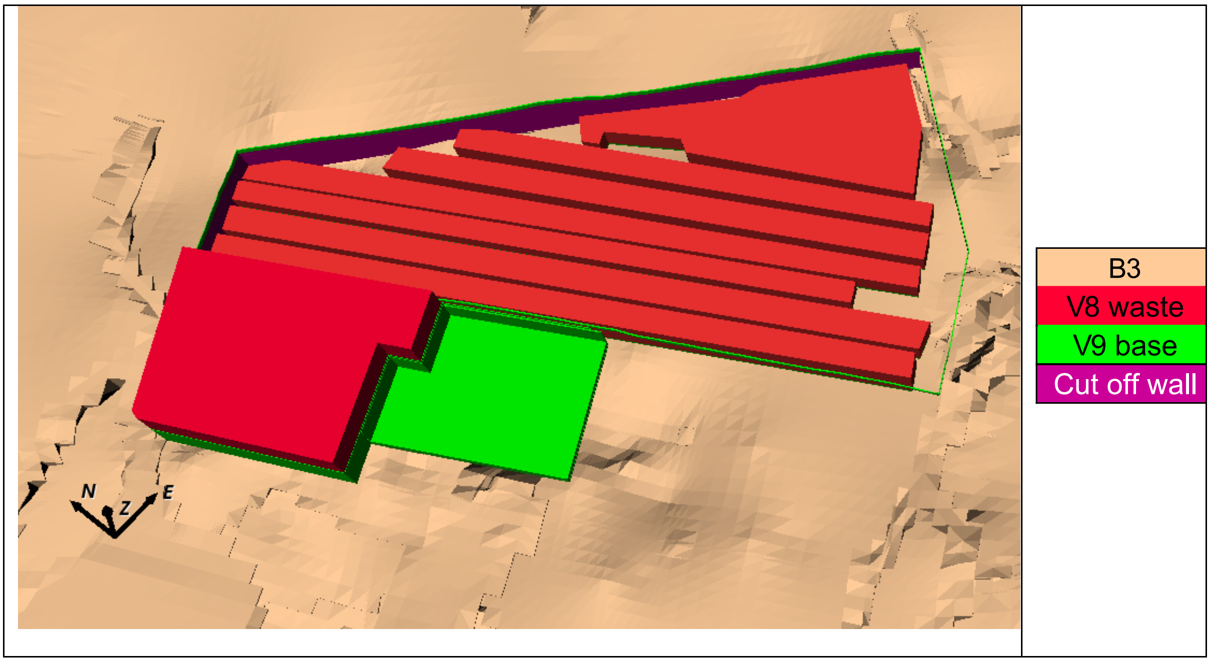


Figure 5.4: **The implementation of the current-day repository engineering as viewed from above. The underlying geology is shown, with the layers above B3 removed. A vertical exaggeration of 5:1 is applied [24].**

The boundary condition on the top surface of the model is used to represent the recharge into the groundwater system. This is the primary mechanism by which water enters the groundwater system. Estimation of the current-day HER and quickflow (see Subsection 4.1.2.1)were obtained using WATBAL [80] and stream-routing models respectively [74]. Values of HER and quickflow were then averaged over the time period from 2011 to 2021 to provide a recharge value for the steady-state models. For the majority of the site-scale model, a mean value for HER of 802 mm y^{-1} and a quickflow proportion of 0.524 are used.

To apply the recharge in the model, a nonlinear boundary condition is employed. This allows water to enter the model when the water table is below ground surface, but not if the water table is at or above ground surface. In areas where the calculated water table is below ground surface, a flux equal to the specified recharge rate (HER minus quickflow) is applied into the model. In areas where the calculated water table is above the ground surface, water is discharged (with a discharge flux proportional to the amount by which the calculated water table is above the ground surface).

5.2.2 Calibration Process and Results Interpretation

One of the largest uncertainties in the hydrogeological model is in the values of the bulk hydraulic conductivities. While parameter ranges for each hydrogeological unit can be suggested based on knowledge of the lithological description of the hydrogeological units, the ranges are often broad due to natural geological variations. To ensure the hydrogeological model provides a good fit to the observed water level measurements on site, a process of calibration is used to provide an optimised representation of the bulk hydraulic conductivities.

The aim of calibration is to infer a set of unknown model parameters, based on a set of real-world observations. In this sense, calibration is a form of inference or inverse modelling. The calibration is carried out for a steady-state model, and therefore the representative heads are time-averaged from water level time-series data, as measured in boreholes. Calibration allows a set of representative bulk hydraulic conductivities to be determined that can be used as a baseline for the current-day model and future model runs. While a calibrated model may give a useful baseline case, it should not be interpreted as a ground-truth. Indeed, there may be multiple models that fit the data to within an acceptable level of accuracy. Thus, after calibration, there remains uncertainty as to the bulk hydraulic conductivities values, referred to as posterior uncertainty.

The PEST software package [112] was used to automate calibration. PEST is an open-source software toolkit for performing model calibration (also called parameter estimation) and model predictive uncertainty analysis, which interacts with a model through the model's own input and output files. When used to undertake parameter estimation, as in the case of the LLWR hydrogeological model calibration, PEST conducts a systematic search of the model's parameter space and runs the model many times, estimating or adjusting its parameters iteratively in an attempt to minimise a calibration objective function.

PEST computes a set of bulk hydraulic conductivity values that minimise the discrepancy between modelled and observed head measurements. These values, shown in Table 5.1, are referred to as calibrated values.

Table 5.1: Calibrated hydraulic conductivities. Units marked with * were not altered in the calibration. Hydraulic conductivities (m s^{-1}) as quoted are converted from permeabilities (m^2) using an idealised conversion factor of 10^7 [24].

Hydrogeological Unit	Horizontal hydraulic conductivity (m s^{-1})	Vertical hydraulic conductivity (m s^{-1})	Notes
A	$2.14\ 10^{-5}$	$3.12\ 10^{-7}$	
B1	$7.91\ 10^{-4}$	$7.91\ 10^{-4}$	Isotropic
Glaciofluvial	$5.01\ 10^{-6}$	$5.01\ 10^{-6}$	Isotropic
Inland Lake*	$1.00\ 10^{-8}$	$1.00\ 10^{-8}$	Isotropic
B3T	$9.53\ 10^{-5}$	$9.53\ 10^{-5}$	Isotropic
B2	$5.36\ 10^{-6}$	$1.55\ 10^{-10}$	
Outwash till	$7.31\ 10^{-6}$	$7.31\ 10^{-7}$	
B3	$9.53\ 10^{-4}$	$9.53\ 10^{-4}$	Isotropic
B3SS	$8.43\ 10^{-5}$	$8.43\ 10^{-5}$	Isotropic
CU*	$1.00\ 10^{-7}$	$1.00\ 10^{-7}$	Isotropic
CL	$2.10\ 10^{-4}$	$1.65\ 10^{-5}$	
D4/D2*	$1.00\ 10^{-7}$	$1.00\ 10^{-7}$	Isotropic
D3*	$1.00\ 10^{-3}$	$1.00\ 10^{-3}$	Isotropic
D1	$3.45\ 10^{-3}$	$3.45\ 10^{-3}$	Isotropic
Helsby Sandstone	$9.21\ 10^{-7}$	$4.89\ 10^{-8}$	
Wilmslow Sandstone	$1.35\ 10^{-9}$	$1.35\ 10^{-9}$	Isotropic
Upper St Bees	$1.12\ 10^{-8}$	$1.12\ 10^{-8}$	Isotropic
Upper BVG*	$1.00\ 10^{-11}$	$1.00\ 10^{-11}$	Isotropic
Upper Granite*	$1.00\ 10^{-12}$	$1.00\ 10^{-12}$	Isotropic
Mudstone*	$1.00\ 10^{-12}$	$1.00\ 10^{-12}$	Isotropic

PEST also provides some corresponding Bayesian uncertainty estimates by approximating the posterior as a normal distribution centred on the calibrated model. These PEST uncertainty estimates were computed alongside the calibration, and most of the results were found to be consistent with the sensitivity analysis, in that the most sensitive parameters were those most effectively constrained by the calibration. In particular, the B3L unit was the most sensitive model parameter and was also found to give the largest information gain (i.e. difference between prior and posterior uncertainty). This is expected since this parameter governs the effective hydraulic conductivities of the aquifer, which in turn dictates the lateral head gradient between the site and the coast. Measurements of the head at monitoring boreholes therefore provide an effective constraint on the permeability of the aquifer.

To interpret the results, we use information from the groundwater flow model, including comparisons between observed and modelled heads (residuals) and pathlines showing the predicted routes by which contaminants are transported from the LLWR. Residuals are the differences between the observed heads measured in the boreholes and the corresponding head values simulated by the model.

The hydrogeological model is expected to directly support the assessment of risks associated with the LLWR, in line with previous hydrogeological models, which were key inputs to 2011 ESC groundwater risk assessment [113, 114] and the groundwater assessment model developed in 2019 [109]. The interpretation of the model results is therefore also assessed in relation to inputs to the assessment model.

5.2.3 Current Day Model Results

Comparison against measured data

The spatial distribution of residuals in A, B2, B3U and B3SSU, and B3L and B3SSL, are depicted in Figure 5.5 for the calibrated model. Positive residuals in the figure show underestimation, while negative residuals suggest overestimation of groundwater heads.

While this model represents heads better than previous models, there are still some locations for which the model fails to capture some aspects of the system behaviour (as specified by the available observed data) due to the complexity of the geological deposits.

To add confidence in the model, the calibrated site-scale model has been run under transient conditions, using a time-varying recharge-discharge boundary condition at the model top surface to represent changes in HER between January 2016 and March 2019. The results of this transient calculation have then been compared against observed borehole hydrographs.

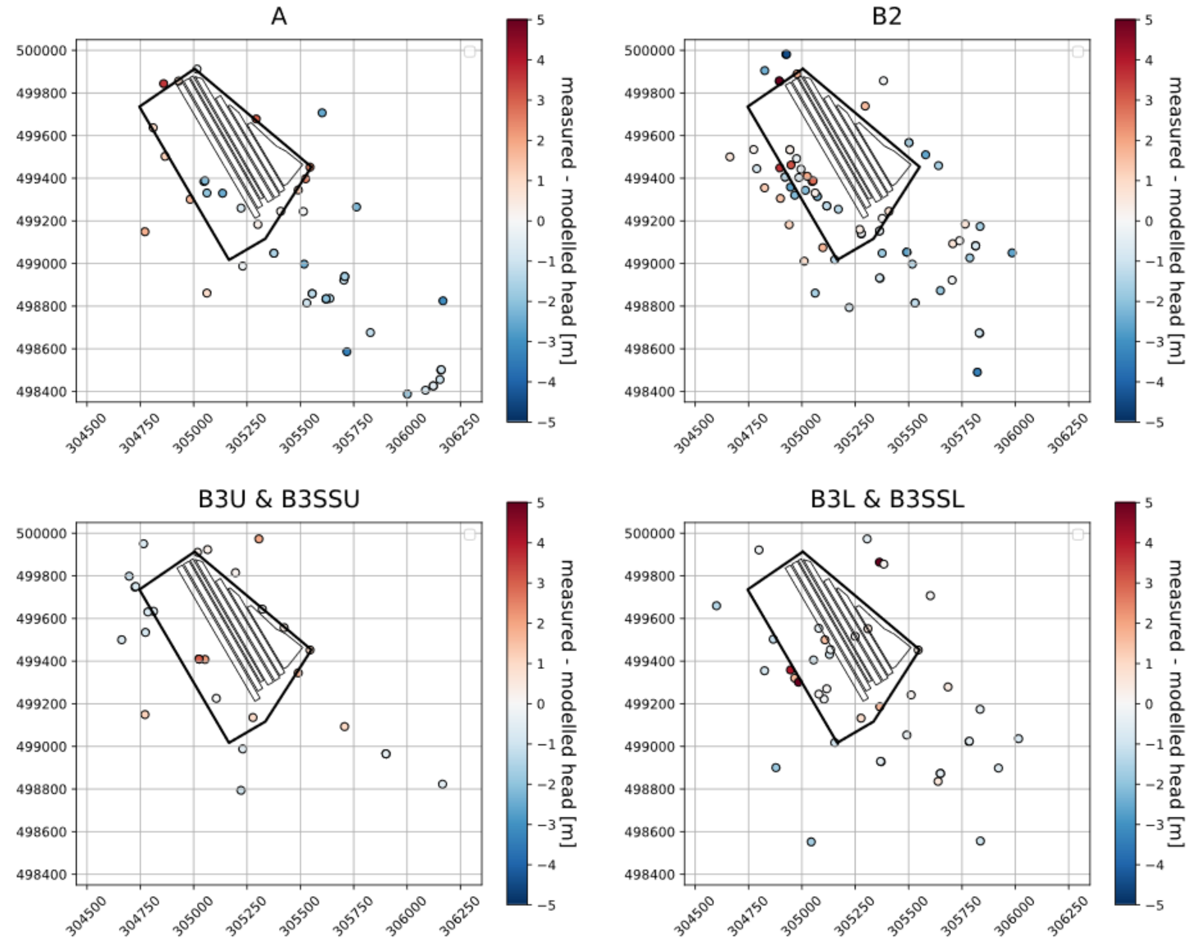


Figure 5.5: Head residuals (measured minus modelled) for the boreholes located in lithological unit A, B2, B3U and B3SSU, and B3L and B3SSL [24].

Hydrographs for three example boreholes are presented in Figure 5.6, showing groundwater levels measured by down-hole dataloggers at various depths. Borehole head results from a transient groundwater flow simulation are also included on the plots. Figure 5.6 shows that while the steady-state head values are not a perfect fit for some boreholes, in part due to the limitations of a homogeneous model, the transient model nonetheless matches the observed seasonal groundwater variations relatively well.

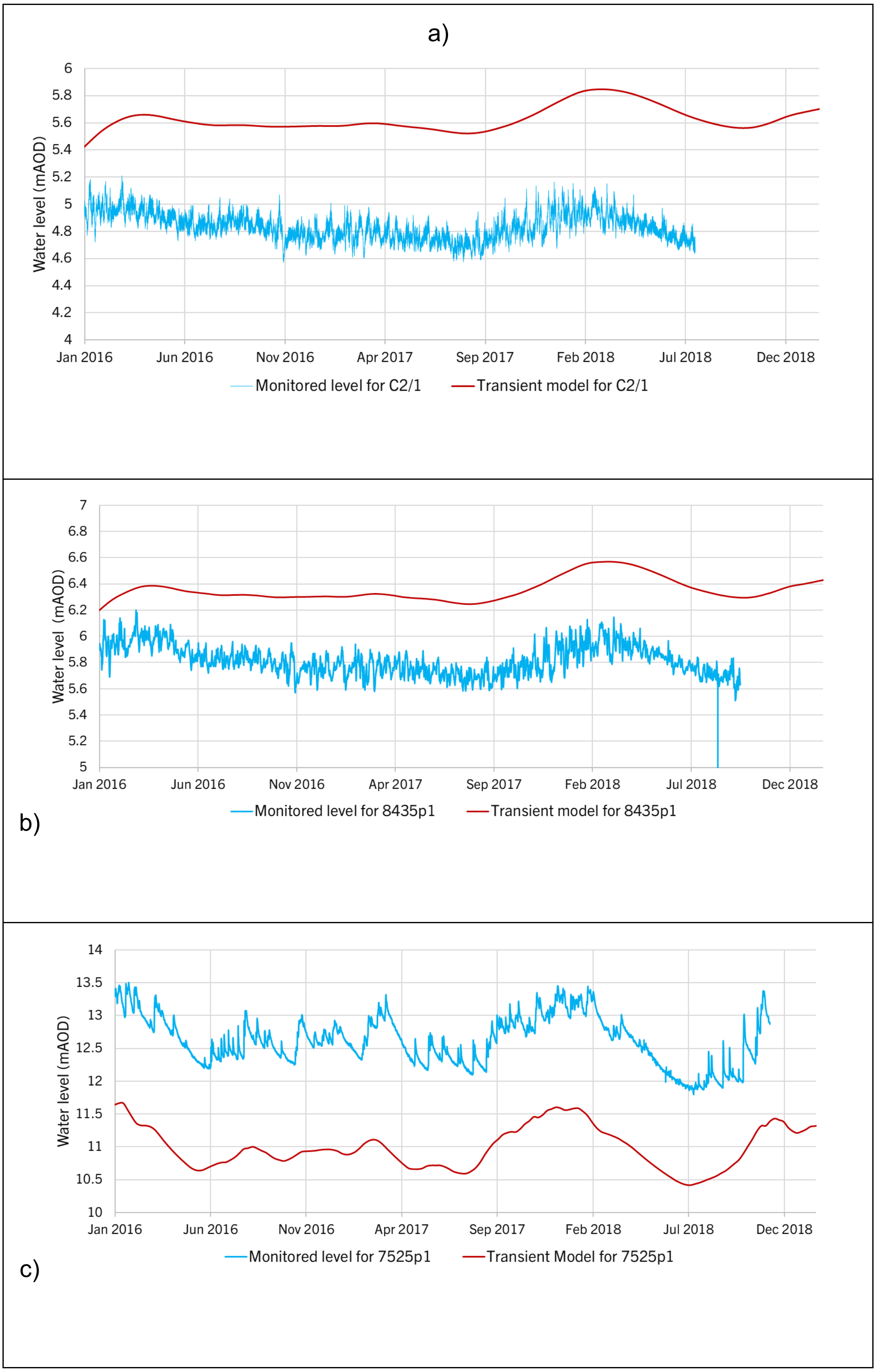


Figure 5.6: **Modelled and measured heads in borehole screen a) C2/1 – hydrogeological unit B3SSB, b) 8435p2 – hydrogeological unit B3L, and c) 7535p1 – hydrogeological unit A [24].**

Pathlines

The hydrogeological model can be used to calculate pathlines for water flow through the repository and the surrounding geology. Pathlines describe the migration of contaminants based on advection alone, i.e. neglecting dispersion, sorption, radioactive decay, and ingrowth. They therefore provide a first indication of the paths that would be followed by contaminants migrating from the waste.

Pathlines are initiated in several locations in the trenches and Vault 8; they are shown superimposed over the lower hydrogeological units in Figure 5.7. The pathlines suggest that most of the groundwater travels from the LLWR through hydrogeological unit B3 to the sea to the west of the model. Figure 5.7 shows the outline of hydrogeological unit B2, demonstrating that that the discharge point for the particles is governed by the offshore extent of unit B2. Figure 5.7 also provides an explanation for the modelled movement of contamination to the north in the offshore region as this is the northerly extent of B2.

As can be seen in Figure 5.8, the contamination is expected to flow mostly downwards in B2 before moving through B3. This is consistent with the hydrogeological models for the 2011 ESC and aligns with the observed concentrations of tritium in groundwater [8] as illustrated by Figure 5.9. Figure 5.10 show the pathlines coloured by time to show the impact of porosity.

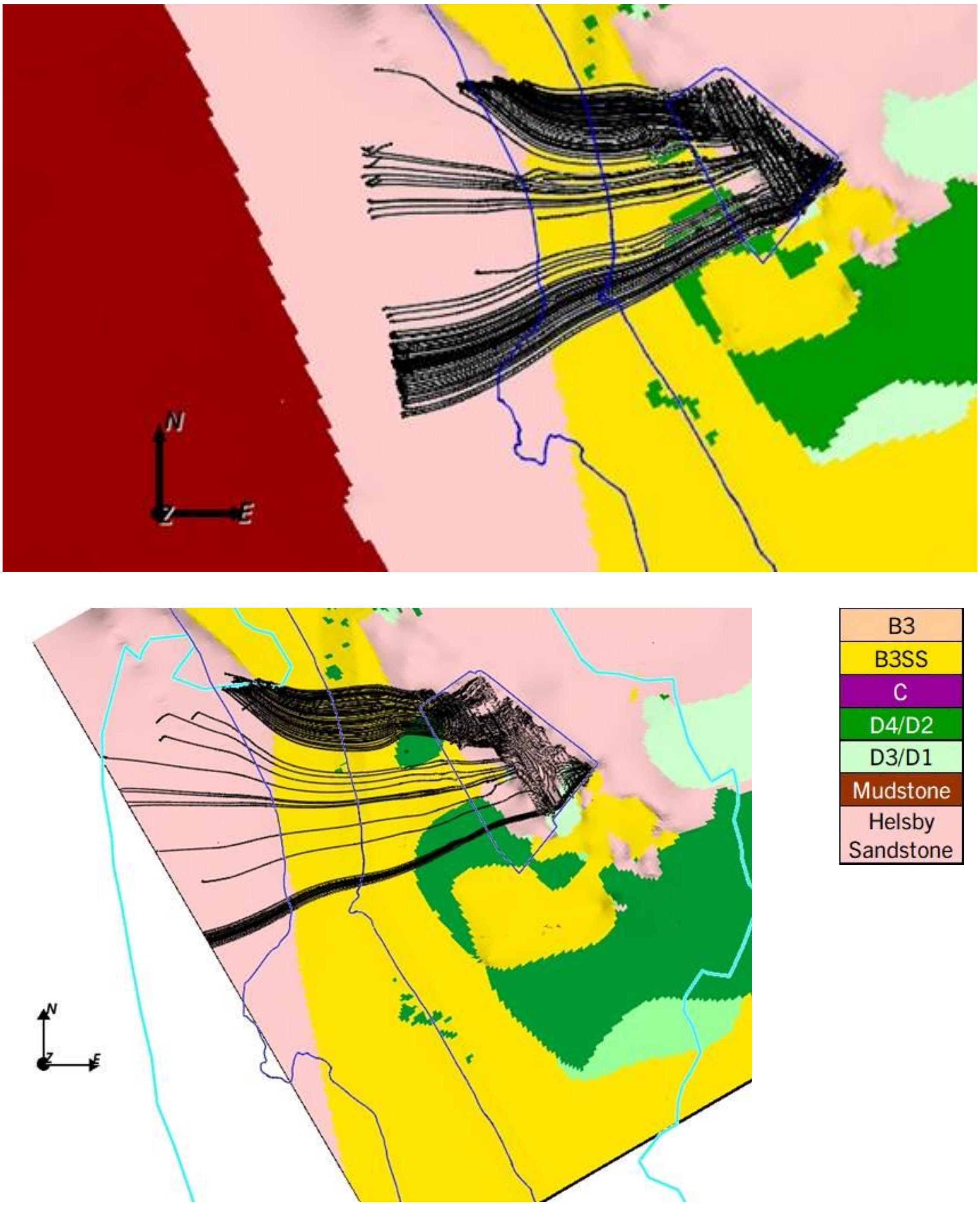


Figure 5.7: Pathlines in the regional- (top) and site-scale (bottom) models shown over the lower hydrogeological units. The approximate extent of unit B2 is delineated by pale blue lines [24].

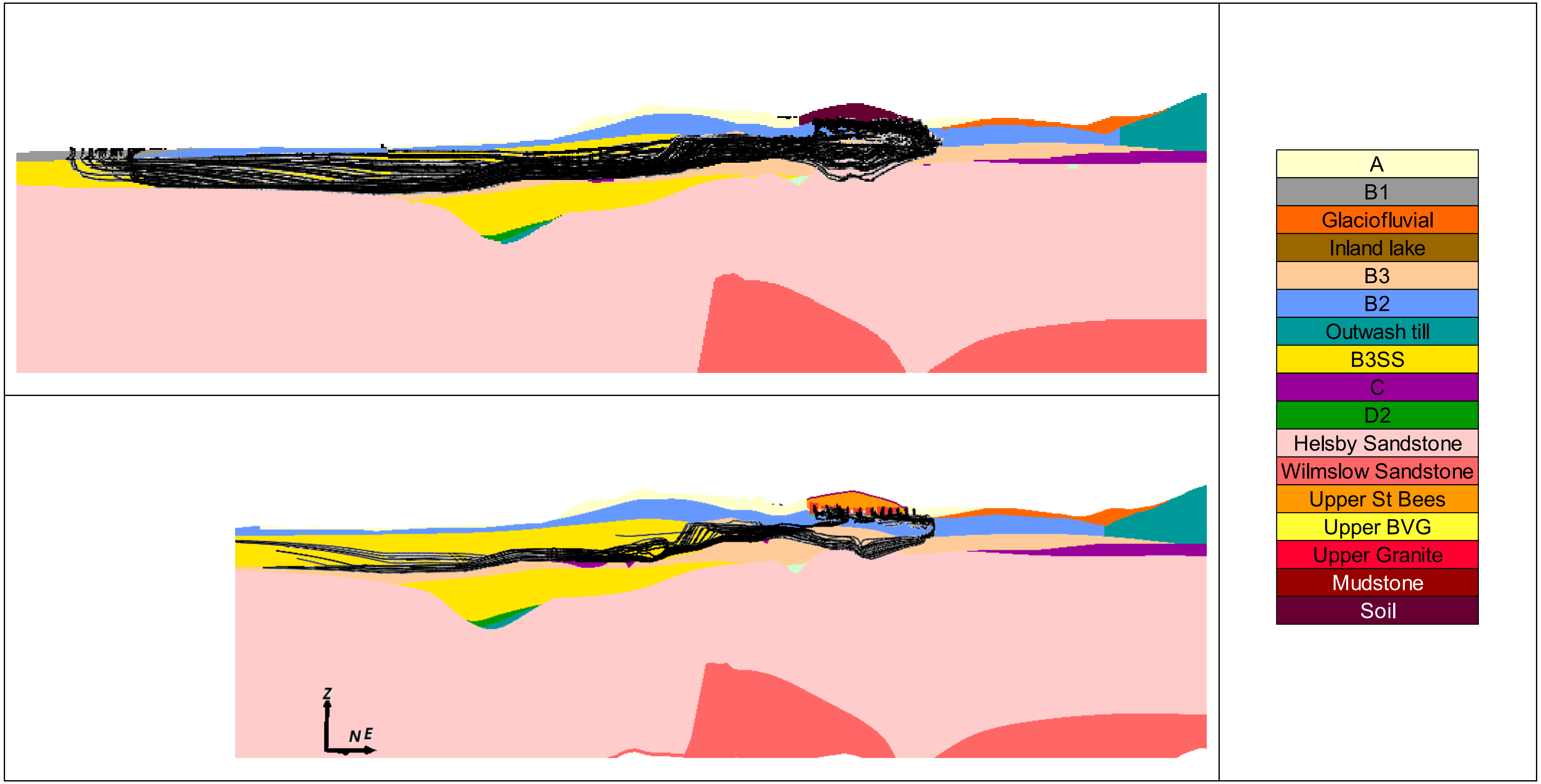


Figure 5.8: Cross-section through the regional- (top) and site-scale (bottom) models (perpendicular to the coast) showing the pathlines in black. A vertical exaggeration of 5:1 is used [24].

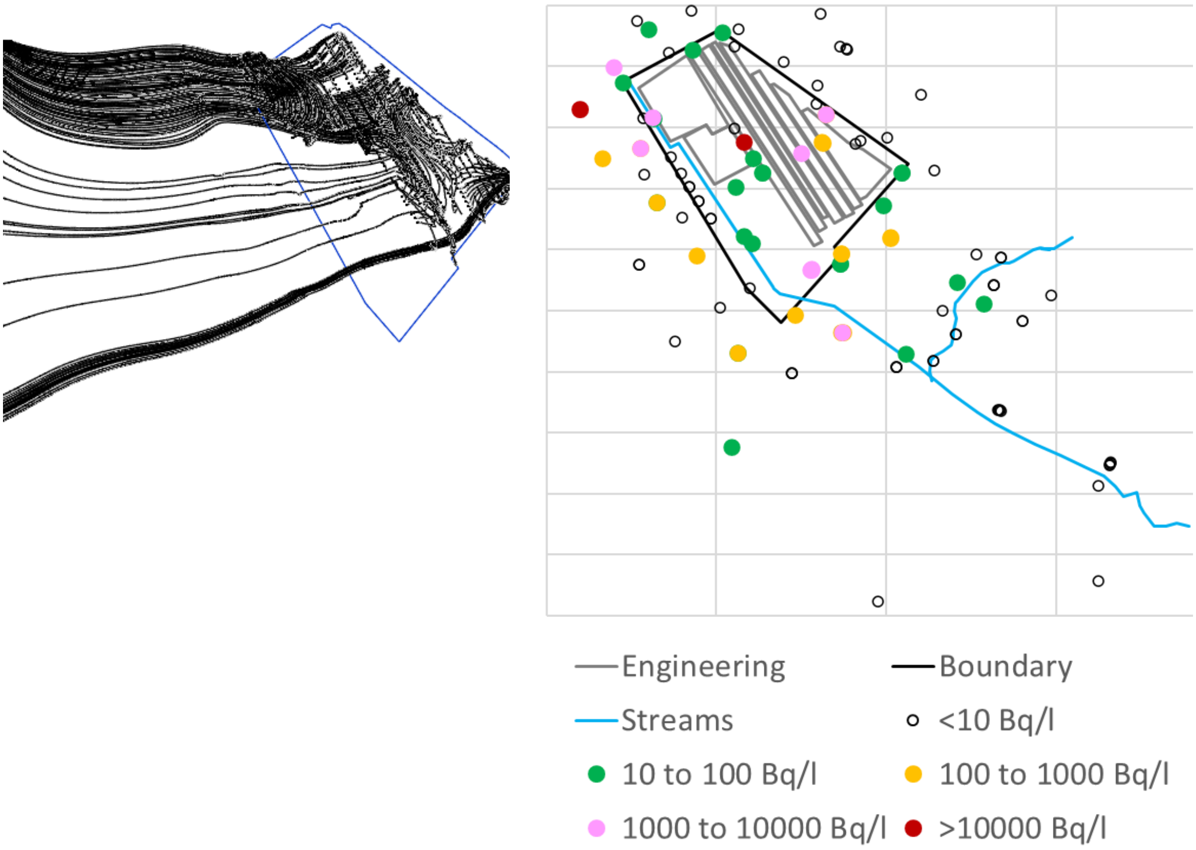


Figure 5.9: Figure showing pathlines from the site-scale model (left) and average tritium measurements across the site (right) [24]

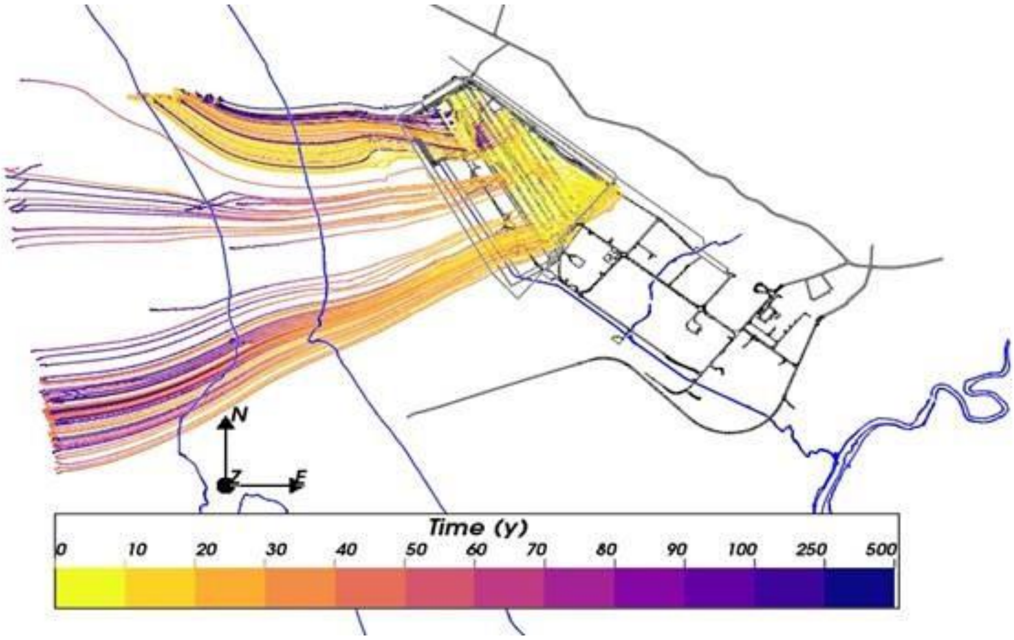


Figure 5.10: Figure showing pathlines from the site-scale model coloured by time to show the impact of effective porosity [24]

Saturation

The model provides an estimate of saturation through the repository and in the surrounding geology (Figure 5.11) at the current time. A saturation of 1 would generally indicate that all the pore spaces were filled with water and that ground would be below the water table. Vault 8 and the profile material over the trenches are shown to not be fully saturated, due to the reduced infiltration applied on them compared with the surrounding areas (reflecting current known conditions). The trenches themselves are however mostly saturated, as is confirmed by data from the probe holes. As seen in Figure 5.11, the geology around the LLWR is mostly saturated but this does not mean that a continuous groundwater body can be inferred. There is a strong vertical gradient in the B2 unit as recorded in the groundwater monitoring data. In the southern part of the site, the higher saturation reflects that the water table is close to the surface as the Upper and Regional Groundwater become indistinguishable. There are near-surface areas that are less saturated, comparison with Figure 5.12 shows that these are in the A and Glaciofluvial hydrogeological units. In areas below the repository where hydrogeological unit B2 is thin, the top of unit B3 is sometimes also not fully saturated.

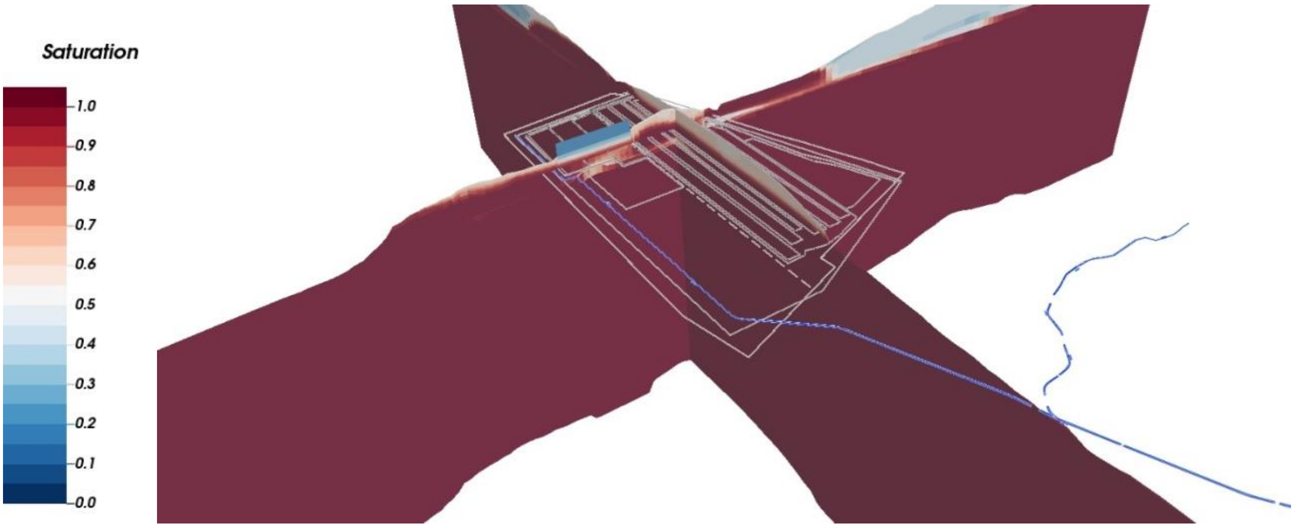


Figure 5.11: Saturation in the site-scale model shown on two slices through the model, one approximately parallel to the sea and one perpendicular to it. An outline of the trenches, vaults and boundary is shown in grey, with streams in blue [24].

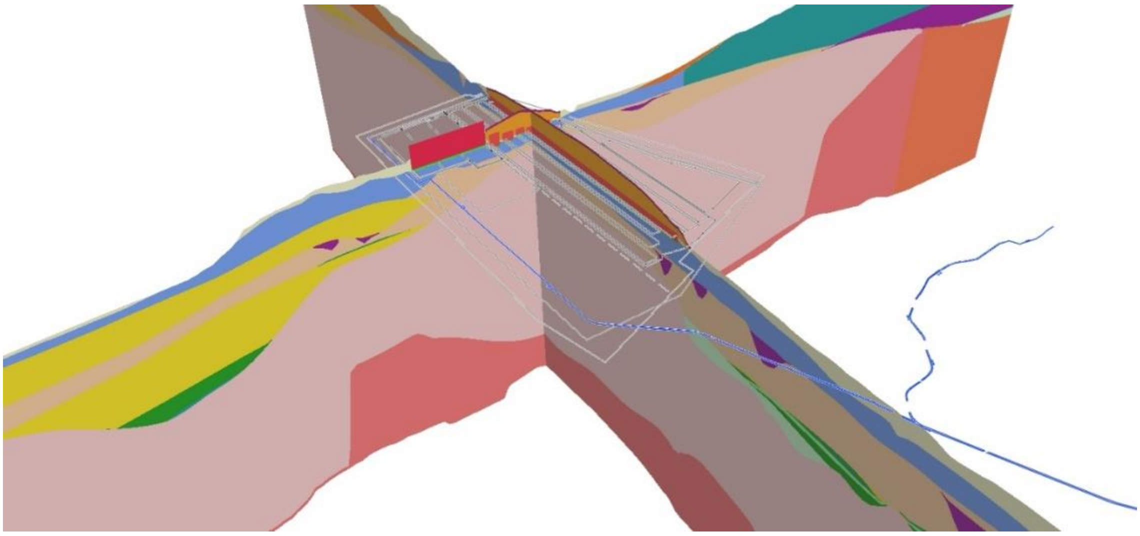


Figure 5.12: Hydrogeological units in the site-scale model shown on two slices through the model, one approximately parallel to the sea and one perpendicular to it. An outline of the trenches, vaults and boundary is shown in grey, with streams in blue [24].

5.2.4 B3 Flow Rates

Flow in the Regional Groundwater is quantified by calculating flow rates within the B3 layer through vertical surfaces perpendicular to the flow direction. Figure 5.13 shows vertical surfaces labelled F1 to F6 positioned upstream and downstream from the repository. The component of the Darcy flux perpendicular to the surface is integrated across the area of each surface within the various layers, to obtain a net flow rate for each layer.

The flow rates are used in the groundwater assessment model to characterise the flows in B3 between the site and the discharge locations at the coast. They are important inputs to the assessment model. Table 5.2 shows the B3 flow rates for the current model as well as for previous models including the model used for the 2011 [75], and the model used to support the 2017 HRA [109].

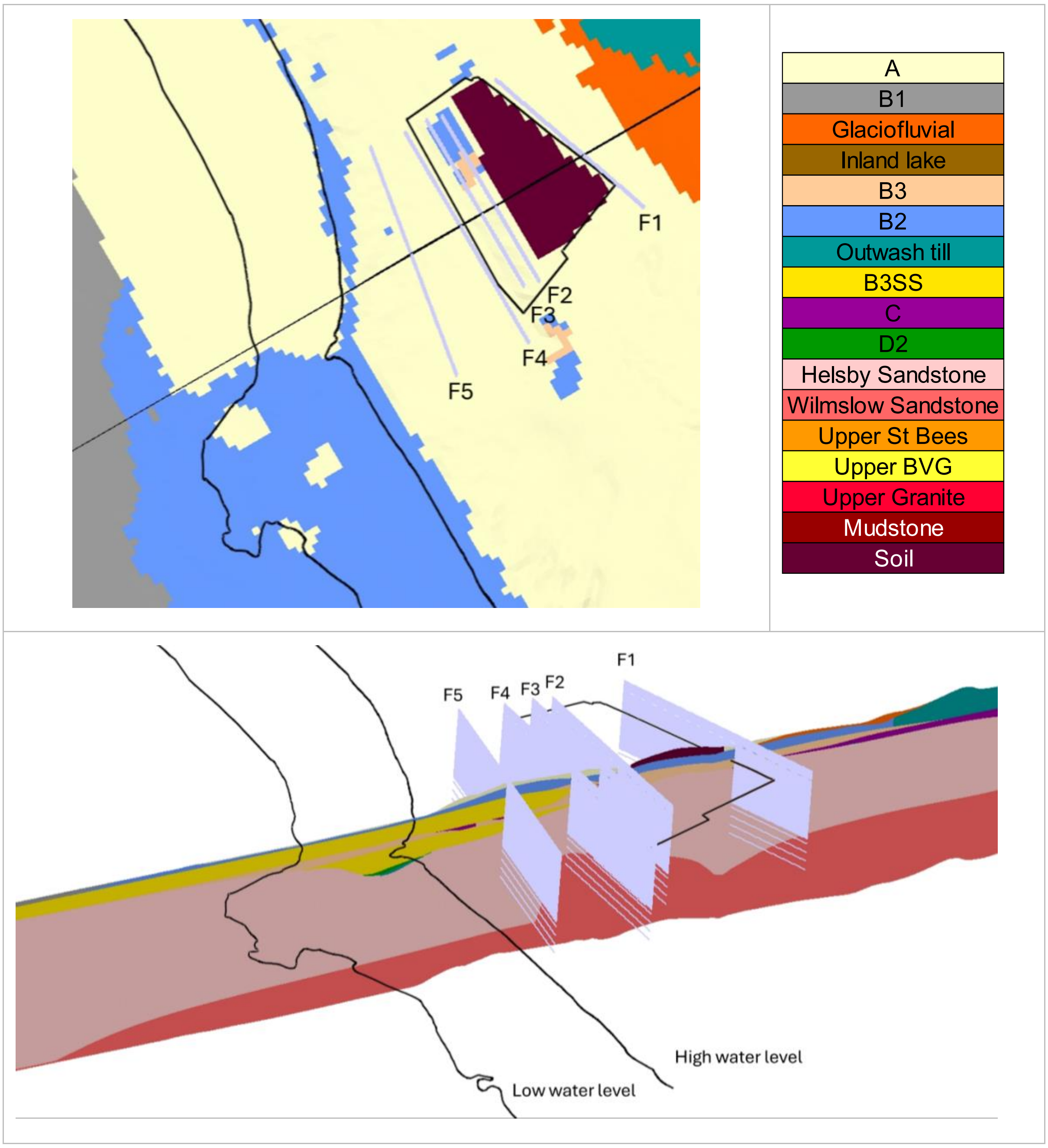


Figure 5.13: Regional model with vertical cross-section showing the F1 to F5 planes. The vertical scale has been exaggerated by a factor of three [24].

Table 5.2: Table showing flow rates in LLWR hydrogeological models for the 2011 ESC [75], 2017 HRA model [109], and current model [24].

Plane	Flow per unit area (m s^{-1})		
	2011 ESC model	2017 HRA model	Current model
F1	1.3 10^{-6}	3.2 10^{-7}	2.2 10^{-6}
F2	9.0 10^{-7}	4.6 10^{-7}	1.1 10^{-6}
F3	1.1 10^{-6}	5.7 10^{-7}	1.0 10^{-6}
F4	1.2 10^{-6}	6.7 10^{-7}	6.9 10^{-7}
F5	1.5 10^{-6}	1.1 10^{-6}	4.5 10^{-7}

The drop in flow rates between the 2011 ESC and 2017 HRA model meant the calculated dilution was less for the well pathway (the risk to people who use water from a well) in the groundwater assessment model. However, the flow rates for the current model suggests that flow rates are now comparable with, or higher than for the 2011 ESC. The one exception to this is the F5 flow rate, which is lower than in previous models. This correlates to the hydraulic conductivity of B3SS below F5, which has a high degree of uncertainty due to the lack of borehole data in this region. In the current-day model, the thickness of unit B3SS also increases between planes F2 and F5, decreasing the overall permeability of the regional aquifer between these planes (as unit B3SS is less permeable than unit B3). This leads to a reduction in the flow rate from plane F2 to F4.

5.3 Hydrogeological Uncertainties

Since the 2011 ESC, work has been undertaken to identify the main uncertainties associated with the geological and hydrogeological environment and take account of them in the groundwater flow and assessment models [39, 115]. There are three sources of uncertainty:

- uncertainty in the geological model;
- uncertainty in the effective properties of the hydrogeological units;
- uncertainty in the hydrogeological conceptual model (independent of the uncertainty in the hydrogeological properties).

Uncertainty in the geological model has been reduced through the collection of new geological data and the reassessment of existing data for available boreholes. This has allowed more value and site conceptualisation insight to be extracted from available site data, thus reducing uncertainty. Changes in the current geological understanding are reflected in updated regional- and site-scale geological models. The updates in the geological understanding have also been incorporated into the hydrogeological models of the site.

Uncertainty studies have been carried out to understand and appropriately quantify the range of possible hydrogeological results. Nine specific uncertainties (some relating to uncertainties in the geological interpretation) were initially identified. An assessment of these uncertainties was carried out to determine the relationship between these key uncertainties and the main aspects of the hydrogeological model. This was used to identify where further work was required to consider the impact of the uncertainty further. These studies were conducted by adapting the current day hydrogeological model to create variant models and considering the range of extreme values for the uncertain parameters. This further work is reported in reference [39]. The key uncertainties considered are as follows.

Values of bulk permeabilities. The values of the bulk permeabilities of different hydrogeological units in the baseline model are set by calibration but the prior distributions are uncertain over a range of many orders of magnitude. The bulk permeabilities of the B3 aquifer sub-units, are expected to be the most significant uncertainty in the hydrogeological model.

Heterogeneity of the B3 aquifer. The hydrogeological model assumes homogenous units, but all geological units will exhibit heterogeneity to a greater or lesser extent. Heterogeneity in the B3 aquifer is expected to have the highest significance for B3 flow rates and spatial distribution of contaminants. The B3L unit is considered to be a glacial outwash deposit, a notably heterogeneous depositional environment composed of braided river channels leading to a complex distribution of sands and gravels.

Bedrock faulting. Several fault zones have been identified in the bedrock, which have the potential to influence groundwater flow, although the widths and permeabilities of these fault zones remains uncertain, and they are not directly represented in the hydrogeological model. While open fractures may provide preferential pathways for flow through the bedrock, faults may also be mineralised or infilled with clay, thus creating a barrier to flow.

Offshore extent of the B2 confining unit. The precise offshore extent of the B2 confining unit is uncertain, leading to uncertainty in the zone of groundwater discharge offshore. The offshore extent of B2 also influences the lateral head gradient in the aquifer, which may affect bulk flow rates.

Layering of the B2 confining unit. The B2 confining unit contains an internal structure of interbedded sand, gravel, and clay-rich layers, which have been associated in the latest geological interpretation with the repeated draining and filling of an ice-dammed lake. While these structures are implicitly included via anisotropy of the bulk permeabilities, the baseline model does not explicitly resolve them.

Near-surface and recharge variability. Near-surface deposits, such as made ground, peat, and alluvium, play a critical role in controlling recharge, surface water interactions, and the characteristics of the upper unsaturated zone. However, because their detailed structure is uncertain, these deposits are combined into a single unit in the baseline model hydrogeological model. Recharge into the model also depends on various uncertain factors such as evapotranspiration and surface water drainage.

Saline intrusion. The LLWR is situated close to the coast, but as groundwater is constantly being replenished by recharge of fresh water from precipitation, groundwater salinity remains low between the site and the coast and has not been represented in the hydrogeological model. However, the interaction between fresh groundwater and saline water from the Irish Sea remains an area of uncertainty and it is important to understand any potential influences of saline intrusion on groundwater flow and contaminant transport.

We have assessed the effects of these uncertainties on bulk groundwater flow rates through the aquifer. Uncertainty in the bulk permeabilities, particularly of the B3 aquifer, is confirmed to be the dominant control on the modelled bulk flow rate.

Beyond bulk flow, we have also examined the effects of heterogeneity on flow focussing and the spatial distribution of contaminated water. Geostatistical structure, together with the contrast between more permeable glacial outwash onshore and less permeable marine sands offshore, can lead to localised flow focussing. Where high permeability features in B3L coincide with low B3SSU permeability, groundwater heads are maintained, and flow is directed into narrow zones. These effects are spatially local and do not affect bulk flow rates but may influence contaminant distribution. Discharge is generally expected offshore, along the boundary of the B2 confining unit. However, some discharge is also possible in the intertidal zone in areas where B2 is thin or discontinuous and vertical connectivity is enhanced. The flow focussing analysis is a first-order approximation and excludes dispersion or dilution effects.

While other factors contribute to variability, their effects are found to be small by comparison with the effect of bulk permeabilities. The results of the corresponding studies for the other areas are summarised below:

- Bedrock faulting: Bedrock faulting has an insignificant impact on groundwater flow. While fault positions are relatively well constrained by geophysical data, there is considerable uncertainty in fault width and permeability, which were treated as primary variables in the analysis. Monte Carlo simulations showed that mean flow rates remain close to those of the no-fault scenario, and the variability introduced by fault-related uncertainties is minimal.
- Offshore extent of the B2 confining unit: Using the baseline model as a starting point, alternative geological surfaces were incorporated to create the alternative models. Figure 5.14 shows the baseline and alternative regional models. Two interpretations of the offshore extent of the B2 confining unit were tested. The alternative model initially produced water levels that were too low, requiring calibration by adjusting B3 permeabilities. Results indicate that uncertainty in B2's offshore extent has little influence on contaminant pathlines or B3 flow rates compared to the dominant effect of bulk permeability uncertainty.

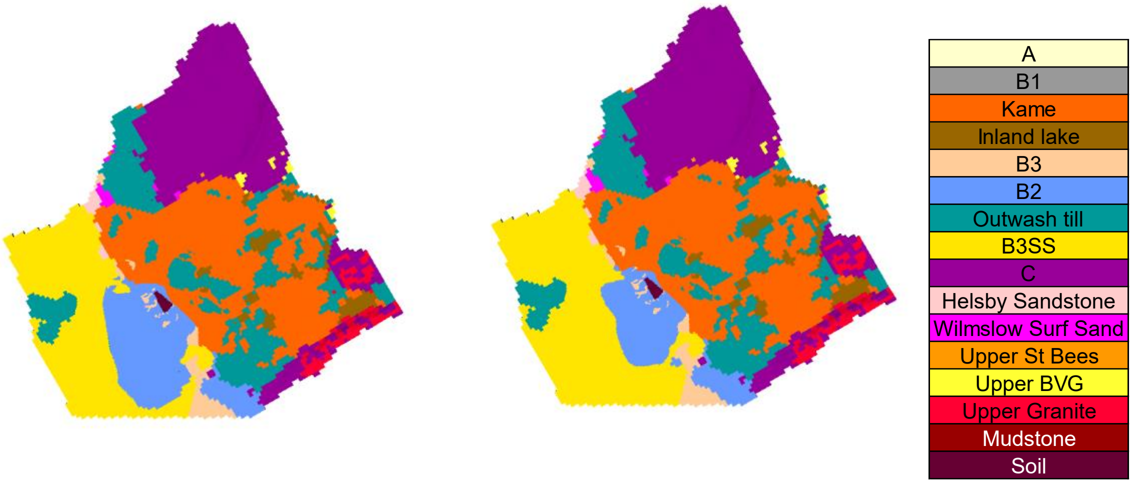


Figure 5.14: Baseline (left) and alternative (right) regional models. B2 is shown in light blue, and units above B2 have been removed from the figure.

- Layering of the B2 confining unit: The baseline hydrogeological model for LLWR represents B2 as a single homogeneous anisotropic unit, simplifying its complex stratigraphy and heterogeneity. A more detailed, layered representation of the B2 unit was incorporated into the model to investigate the potential impact of this internal structure. Seven alternating clay and sand layers were used to consider uncertainties in permeability distribution and connectivity. While an extreme permeability scenario increased groundwater movement and beach discharge, it was unrealistic and contradicted observed head gradients. Overall, uncertainty in B2 layering has minimal effect on regional flow variability.
- Near-surface and recharge variability: To account for the variability in hydrogeological unit A, it was subdivided into upper and lower alluvium with a peat layer in between acting as a barrier to vertical flow in some areas. The heterogeneity of these materials presents challenges in defining consistent hydrogeological properties, particularly due to variations in hydraulic conductivity between low permeability peat and more permeable alluvium. Variations in this structure produced negligible changes in B3 flow rates. A supplementary analysis combining recharge and permeability uncertainties also showed minimal impact on bulk flow variability. These factors may be relevant for local-scale assessments but are not significant at the regional scale.
- Saline intrusion: Simplifying assumptions were made to facilitate numerical modelling, most notably by setting boundary conditions that force the saline transition zone to intersect the coastline, and by setting an unrealistically high salt diffusion coefficient to ensure numerical convergence. These assumptions likely underestimate the freshwater zone extent, but results align with previous studies

[116, 117] and confirm that saline intrusion does not significantly affect bulk groundwater flow rates relevant to the ESC.

Figure 5.15 illustrates the flow rate distributions for each of the studies, displaying the relative impact of each uncertainty. It also includes an estimation of the total variability in flow rates which takes into account all of the different factors. These data are used as a basis for representing uncertainty in the groundwater risk assessment model. Individual uncertainty contributions to B3 flow are quantified separately and expressed as variances in log space. These variances are then summed to derive a single combined log-normal distribution for bulk B3 flow. This approach provides a conservative and transparent approximation of total hydrogeological uncertainty while remaining consistent with observed groundwater heads and suitable for use within the probabilistic groundwater assessment.

The combined uncertainty distributions are dominated by the two largest contributors, namely bulk permeability and heterogeneity. Uncertainty associated with bulk permeability alone is almost equivalent to the total combined uncertainty that includes all sources. Figure 5.15 also shows the range of flow values from previous models of the LLWR, collated from multiple studies carried out since 2010. This range is covered by the total combined distributions for planes F1-F4, but this is not the case for F5 where the mean flow rate is notably lower than the lowest previous model which was the HRA model. The lower F5 flow rates as observed in the model presented here may be primarily explained by changes in the geological model to the extent of B3SSU together with a high degree of uncertainty regarding the permeability of B3SSU.

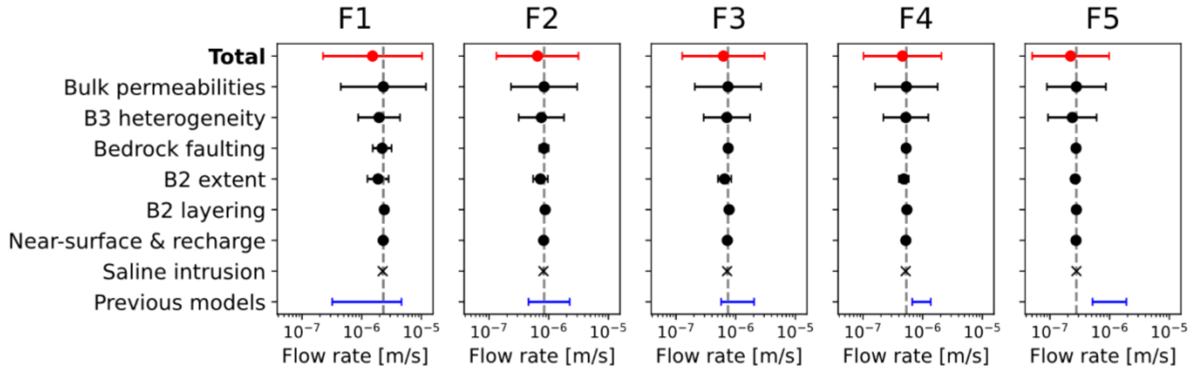


Figure 5.15: Combined flow rate distributions (red) plotted together with the individual components (black). Dashed grey line shows the baseline model, defined as the posterior mean of the bulk permeabilities study. Red and black intervals show two standard deviations about the mean, while the cross indicates the results of the saline model, which does not have an associated uncertainty. Blue interval shows range of flow rates as predicted by previous models of the LLWR since 2006.

The final distributions are well approximated by log-normal forms with $\log_{10}$ standard deviations approximately in the range 0.3 to 0.45, indicating bounding estimates of around ten times faster or slower than the mean, which is consistent with variations in flow rates considered in the groundwater assessment model. Whilst there are variations in flow paths associated with these uncertainties, we can demonstrate that the overall pattern of flow is unaffected and that the representation of the groundwater pathway in the safety assessment is robust.

5.4 3-D Model of Post-closure Flows

The groundwater assessment model is run over a period starting with construction of the LLWR until the point at which the coastline intersects the site as a result of coastal erosion. This period is expected to last around 1,000 years. It is expected that there will be coastal erosion, changes in climate, and changes in the performance of the engineered materials over this period.

Following the same approach as was used in the 2011 ESC, a series of snapshot future hydrogeological models have therefore been produced to provide input to the groundwater assessment model. The '*Site Evolution*' report [7] provides more details on the work done to understand the effects of climate change on the site. The supporting climate change study [118] identifies three emissions scenarios that have been used to capture the range of possible future greenhouse gas pathways:

- a reference emissions scenario, where CO_2 emissions remain around current levels until the middle of the twenty-first century, before decreasing;
- a low emissions scenario, where CO_2 emissions decline to net zero after 2050, followed by net negative CO_2 emissions;
- a high emissions scenario, where CO_2 emissions roughly double from current levels by 2050 and peak at three times current levels in around 2090.

Each scenario has associated projections for sea-level rise, temperature, precipitation, evapotranspiration, and coastal erosion which are incorporated into the snapshot models. Six snapshot times have been selected as illustrated in Table 5.3 The models use the same domain as the Current Day Model described in Subsection 5.2 but incorporate climate related changes and the changes in the as-built engineering.

The climate study provided information on changes in precipitation and potential evapotranspiration over time, in terms of percentage changes compared with the baseline value, as shown in Table 5.4. Timescales for the time taken for the coastline to erode to the repository are defined for each climate scenario in [118]. These are shown (interpolated to the snapshot times) in Table 5.5.

Table 5.3: Table of times for snapshot models

Snapshot times (AD)	Description
2130	As-built (facility at closure)
2230	100 years after as-built (potential end of institutional control)
2430	300 years after as-built (potential end of institutional control)
2780	650 years after as-built (similar to high emissions scenario erosion time)
3280	1,150 years after as-built (similar to reference scenario erosion time)
3780	1,650 years after as-built (similar to low emissions scenario erosion time)

Table 5.4: Table showing percentage change in precipitation (P) and potential evapotranspiration (PE) quoted to the nearest % at various times for different emissions scenarios (from reference [118]).

Climate scenario	Parameter	Time after present				
		100 y	**300 y**	**1000 y**	**3000 y**	**10000 y**
Reference	P	4%	4%	4%	3%	3%
	PE	13%	13%	13%	11%	9%
Low emission	P	2%	2%	2%	1%	0%
	PE	7%	7%	6%	4%	0%
High emission	P	7%	9%	15%	12%	6%
	PE	22%	29%	48%	39%	19%

Table 5.5: Sea-level rise and coastal erosion for different dates and emissions scenarios

Date	Sea level rise (m)			Coastal erosion (m)		
	Reference	Low	High	Reference	Low	High
2130	1.1	0.4	1.6	47	33	78
2230	2.1	0.8	2.9	91	65	150
2430	3.4	1.2	6.3	178	127	296
2780			11.6			550
3280	5.6			550		
3780		1.7			550	

Coastal erosion is applied to the hydrogeological model by modifying the topography offshore in a similar manner to the 2011 ESC. This involves:

- translating the base of the Drigg Beach cliff horizontally by the coastal advance distance (at an angle assumed to be perpendicular to the coastline);
- translating the base of the Drigg Beach cliff vertically by the sea-level rise;
- altering the seabed surface with a linear mapping so that it links the base of Drigg Beach cliff and the old seabed surface.

These resulting surfaces are shown for the reference scenario in Figure 5.16. Four models were created for each emissions scenario, spanning the time from 2130 to the point at which the coastline reaches the facility.

The engineering of the LLWR site is updated in the model, in line with our '*Engineering Design*' report [5], within the future hydrogeological models to reflect:

- expected changes to the engineered components such as the constructions of Vault 9a and Vault 10 to 12 and extension of the cut-off wall;
- representation of planned waste stacking within the vaults;
- addition of the final cap and infiltration through the capping material;
- changes in the hydraulic conductivities of engineered materials over time.

Figure 5.17 shows the additional vaults and extension of the cut-off wall.

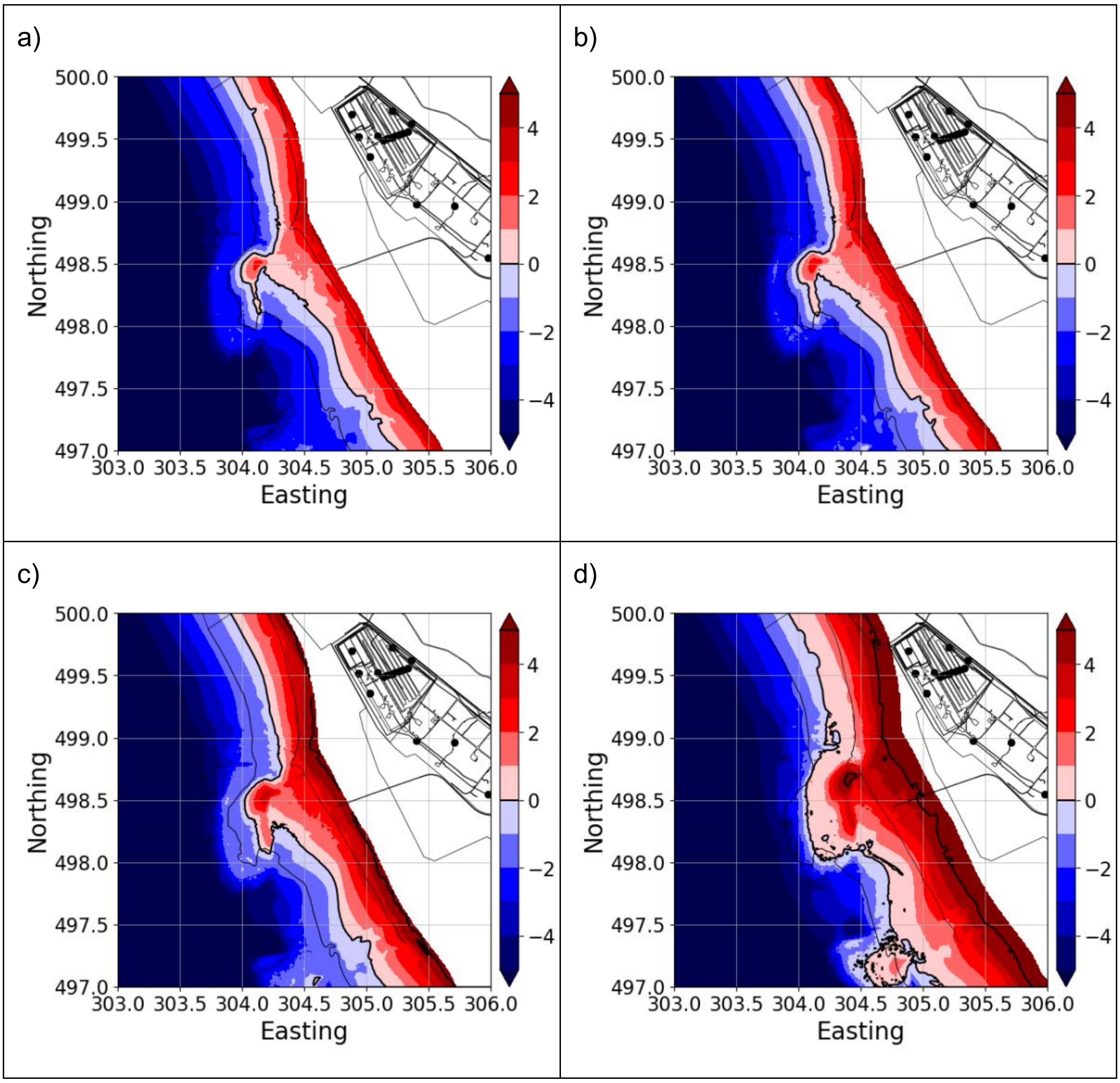


Figure 5.16: Updated coastal surface for reference emissions scenario for snapshot times a) 2130, b) 2230, c) 2430, d) 3280. Coastal surface (coloured region) is the offshore region up to the Drigg Beach cliff. Elevation is relative to current-day sea level. Black lines indicate 0 and 5 m contours [24].

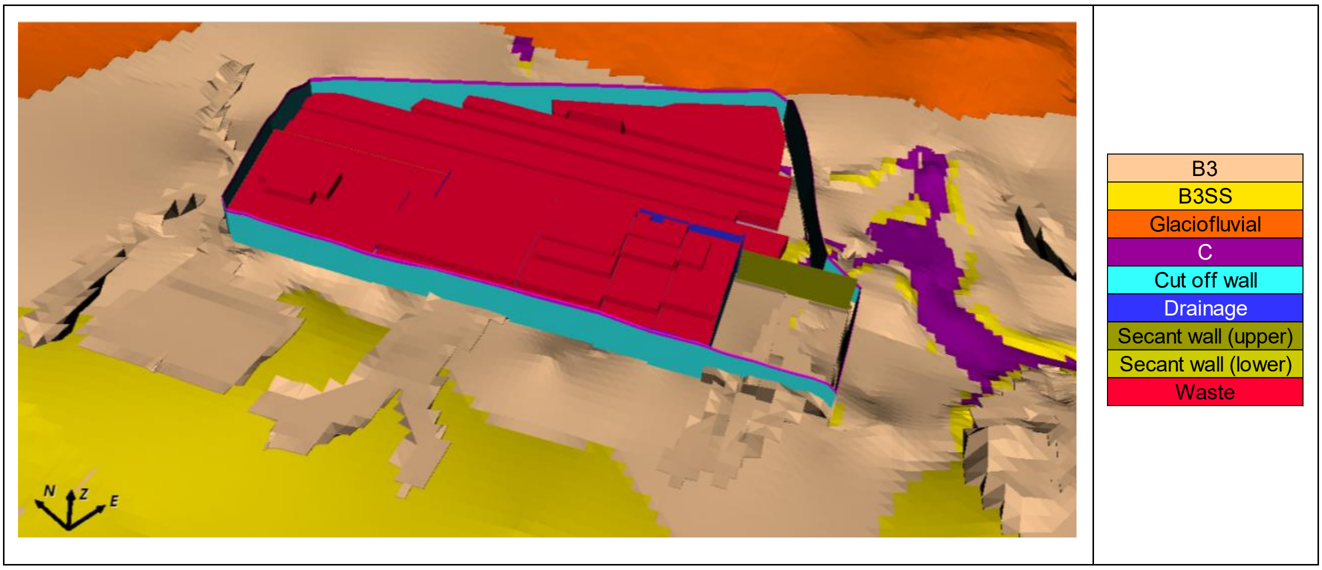


Figure 5.17: View from south-west showing the vault and trench waste volumes, vertical vault drainage material and cut-off wall. A vertical exaggeration of 5:1 is used [24]

The evolution of the parameters of the engineered features is taken from the EPA [79]. This considers how materials like concrete will evolve over the time period. The values from the EPA were interpolated to the snapshot times before being applied to the hydrogeological models. Within the EPA, a significant amount of work was conducted to understand the evolution of the infiltration through the final cap [119]. The infiltration model is a layered model that better reflects the cap's actual construction and degradation pathways and incorporates probabilistic and deterministic calculations, accounting for uncertainties in material properties, degradation rates, and climate scenarios. 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. This has reduced the predicted infiltration rate significantly compared with the 2011 ESC and in the central probability case it remains low throughout the time period that is being modelled. Table 5.6 shows the infiltration rates used in the future models and the equivalent infiltration rates used in the 2011 ESC. The snapshot times used are different reflecting the expected extended closure timeframe. The model uses the central (median) infiltration projections from the distributions.

Using particle tracking, the models indicate that most groundwater originating from the LLWR travels through hydrogeological unit B3 towards the sea, generally discharging offshore where unit B2 ends. As time progresses and the coastline recedes, a greater proportion of groundwater is drawn northwards, particularly as unit B2 thins in that direction as illustrated in Figure 5.18 and Figure 5.19 for the reference emissions scenario and Figure 5.20 and Figure 5.21 for the low and high emissions scenarios respectively.

Table 5.6: Change in infiltration over the cap for future times [119].

Snapshot times (AD)	Equivalent 2011 ESC Recharge over the cap (mm y^{-1})	2026 ESC Recharge over the cap (mm y^{-1})
2130	1	0.002
2230	10	0.002
2430	-	0.004
2780	-	0.011
3280	200	0.027
3780	219	0.286

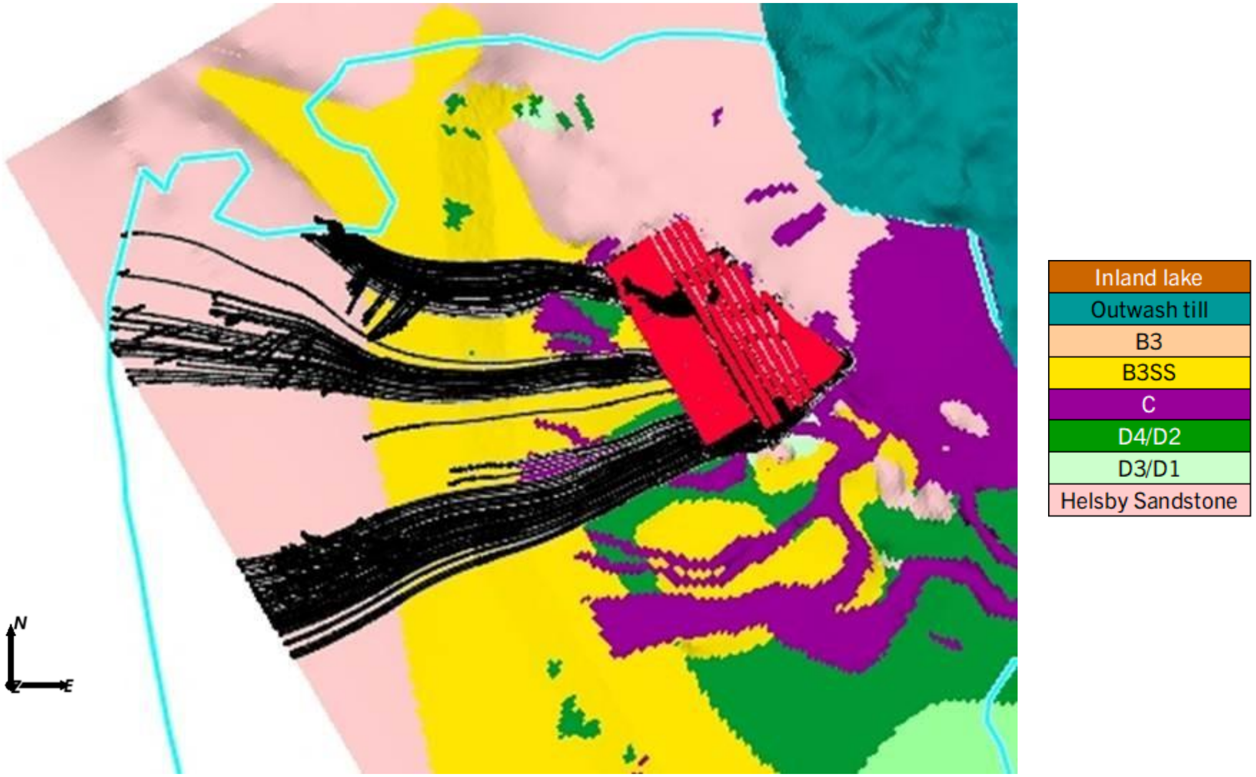


Figure 5.18: **Surface view of the pathlines (in black) for the 2130 reference climate model overlaid over the deeper units. The approximate extent of unit B2 is shown in pale blue [24].**

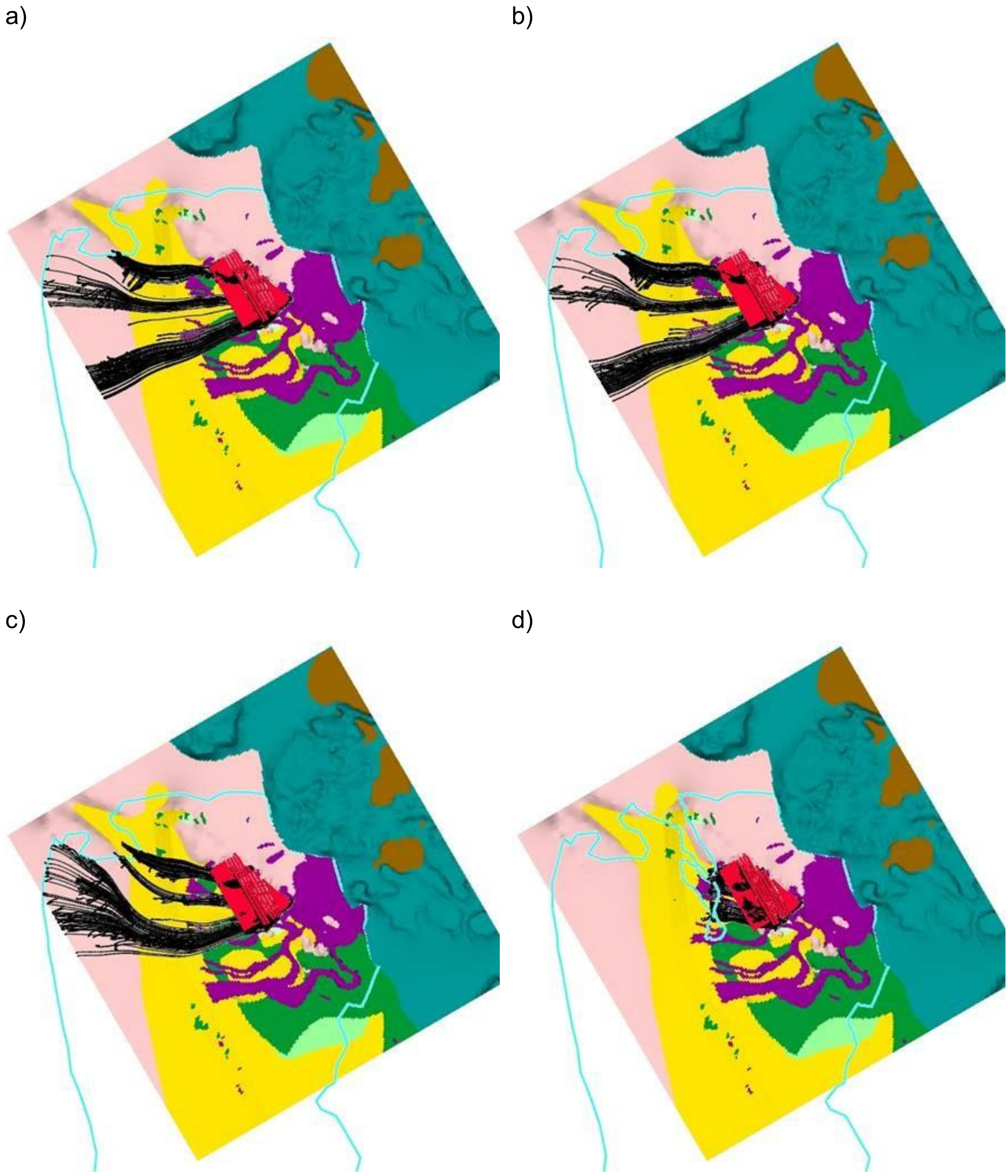


Figure 5.19: Surface view of the reference scenario models showing the pathlines (in black) from the site overlaid over the geology for a) 2130 AD, b) 2230 AD, c) 2430 AD, and d) 3280 AD. The approximate extent of unit B2 is shown in pale blue [24].

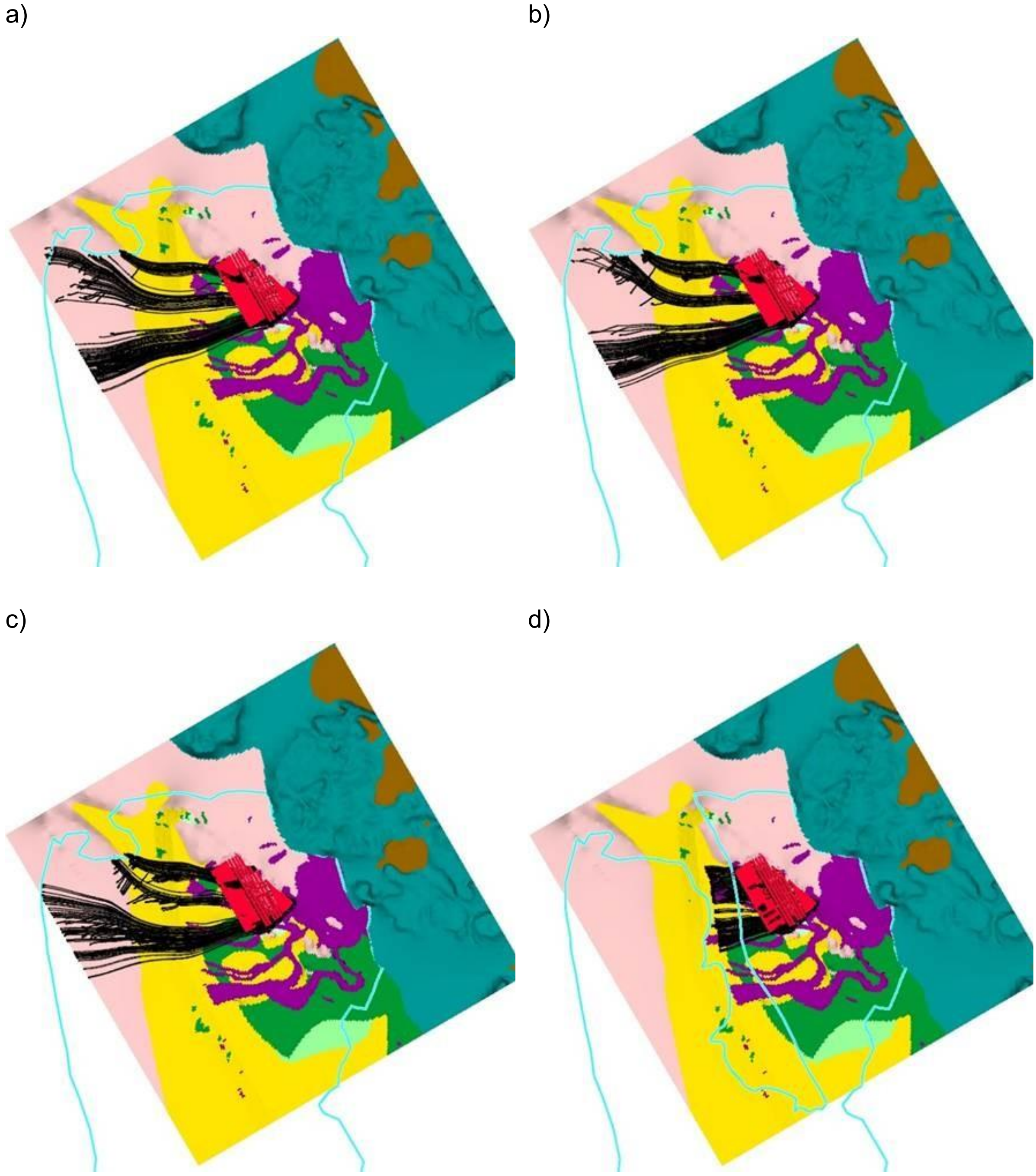
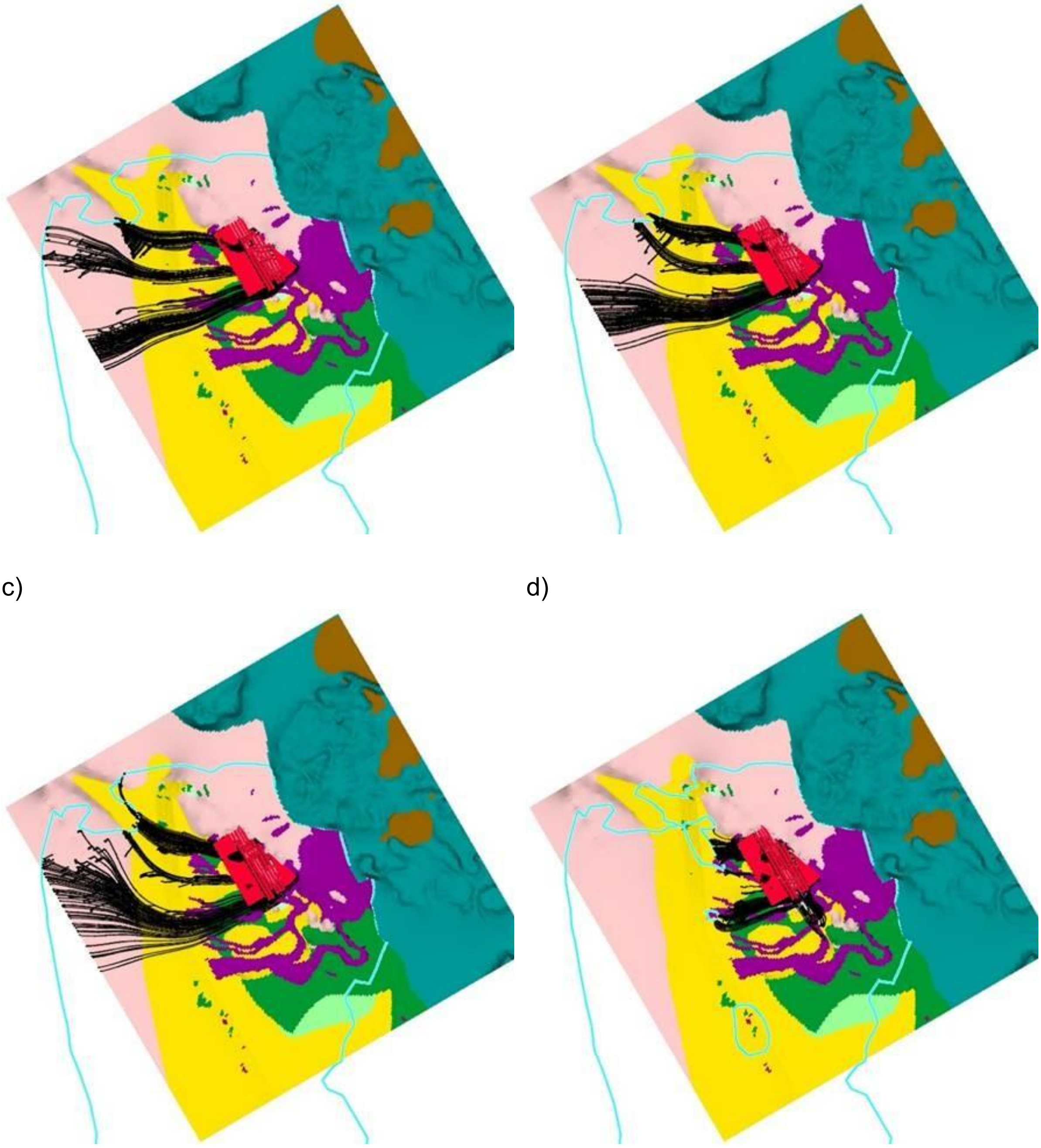


Figure 5.20: Surface view of the low emissions scenario models showing the pathlines (in black) from the site overlaid over the geology for a) 2130 AD, b) 2230 AD, c) 2430 AD, and d) 3780 AD. The approximate extent of unit B2 is shown in pale blue [24].



a)

b)

c)

d)

Figure 5.21: Surface view of the high emissions scenario models showing the pathlines (in black) from the site overlaid over the geology for a) 2130 AD, b) 2230 AD, c) 2430 AD, and d) 2780 AD. The approximate extent of unit B2 is shown in pale blue [24].

Under the high emissions scenario, there is increased groundwater movement to the south-east, with some areas eventually lying below sea level, suggesting significant geomorphological and hydrological changes as shown in Figure 5.22.

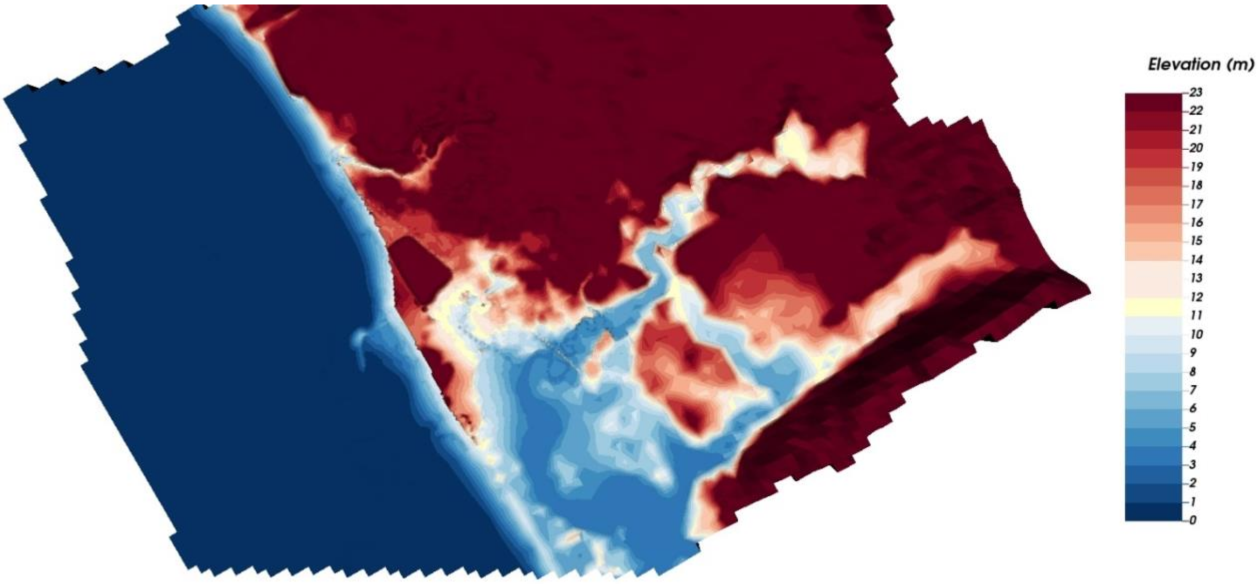


Figure 5.22: Surface view of the 2780 high emissions scenario regional model, coloured by elevation (where red is above sea level, blue is below and yellow is sea level for this model) [24].

The model results show a general trend of reduced saturation beneath the repository over time, especially in the reference and low emissions scenarios, due to the effects of the final cap and coastal erosion, as shown in Figure 5.23. In high emissions scenarios, rising sea levels can lead to increased saturation, especially in the lower vaults, and even in the lower parts of waste in the deepest vaults (e.g. Vault 12). The saturation of the vault bases is closely linked to their elevation relative to local geology, with lower vaults remaining more saturated.

Assessment of flow rates in the B3 hydrogeological unit across different models and scenarios reveals a gradual decrease in flow rates over time, particularly in low and reference emissions scenarios. Reduced groundwater movement arises as coastline retreat shortens flow paths and reduces the hydraulic gradient between recharge areas and the coastal discharge boundary. This leads to lower groundwater velocities and bulk flow rates in the B3 aquifer, particularly in low and reference emissions scenarios where coastal retreat progresses gradually and without compensating increases in driving head.

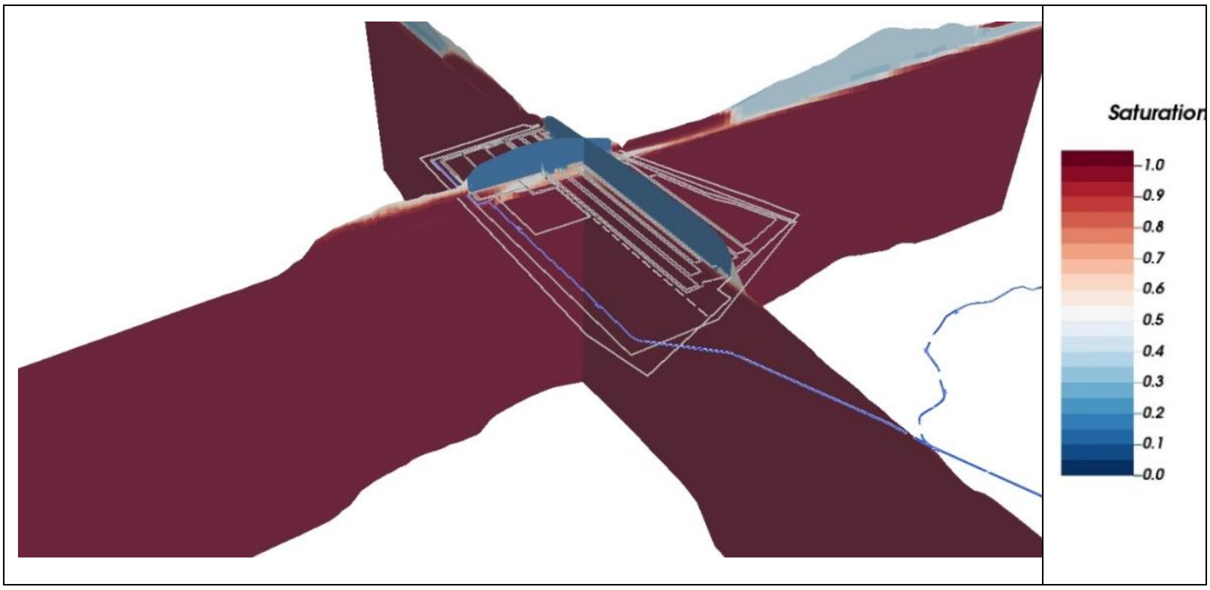


Figure 5.23: Saturation in the 2130 reference climate site-scale model shown on two slices through the model, one approximately parallel to the sea and one perpendicular to it. An outline of the trenches, vaults and boundary is shown in grey, with streams in blue [24].

5.5 Compartment Flow Model

The primary interaction between the hydrogeological modelling and the groundwater assessment model is through the CFM. In terms of flows through the near field and the B2 hydrogeological unit, the relevant interface is the CFM. The CFM provides a simplified representation of the evolution of flows and water levels within the LLWR, enabling tasks that the full ConnectFlow model cannot efficiently handle such as probabilistic simulations. It consists of a few hundred compartments whereas the ConnectFlow models have millions of finite elements. The CFM has a smaller domain than the finite-element model, extending vertically from the repository down to the B2 geological layer and laterally to a small distance outside of the cut-off wall. The primary outputs are the evolution of water levels in each compartment and the flows between pairs of compartments. The development of the model has been guided by understanding gained from the more detailed 3-D groundwater flow simulations using the more complex 3-D finite-element ConnectFlow models. This includes calibrating the repository water levels in the CFM against those in the ConnectFlow model and using data from the ConnectFlow model to define the CFM fixed-head boundary condition, applied at the bottom of the model (base of unit B2) to represent the regional groundwater head.

The model represents flows down through each compartment and flows between the compartment and overlying or underlying compartments and the adjacent compartments, with mass being conserved for each compartment. The downwards flow through a compartment is through one or more horizontal layers of different materials within the compartment. The lateral flows between adjacent compartments may reflect the influence of different materials at different levels within the compartment, as well as the presence of contrasting materials at the edges, such as walls or drains. Fixed-head boundary conditions in the CFM (at the base of unit B2) are set using average heads from the ConnectFlow model.

A plan view from above is shown in Figure 5.24. All compartments in each stack have the same 2-D footprint, which can be any polygon. The base and top of a compartment are horizontal. The compartments completely fill the 3-D domain of the model, with no gaps between. Figure 5.25 shows a cross-section through Vault 11 and neighbouring Trench 3 (other trenches are omitted in the image for simplicity). More detail on the CFM is provided in the hydrogeological modelling report [24]. The equations that govern the CFM are described in detail in the 2019 groundwater assessment model report [109]. These equations can be summarised as a statement of water mass balance. The CFM is implemented in a Fortran Dynamic Link Library (DLL), which calculates the equilibrium flows and compartment water contents for a given set of input parameters representing a single timepoint. The DLL is embedded in the GoldSim model, with the latter managing input data and output of results from the DLL. The output extracted from the DLL for each timestep is combined into a time series for a given deterministic or probabilistic case. It is noted that this is a series of steady states and not a fully transient calculation that takes into account hydraulic storage.

The hydraulic conductivities of engineered components at the LLWR were elicited and documented in reference [120] for the 2011 ESC. This reference has since been superseded by the EPA although some properties listed in the EPA have kept the values stated in the 2011 elicitation.

The degradation of the engineered components over time requires that the hydraulic conductivities be specified as a function of time. The uncertainty in these values must also be considered. The EPA approaches this by specifying probability density functions for each conductivity at specified points in time (although in some cases a deterministic value is provided instead).

In the groundwater assessment [14], changes in the infiltration rate through the cap have been used to consider deterministic cases for best estimates of the onset of membrane degradation and to explore poor cap performance. A probabilistic case, in which we sample over the cap infiltration probability density functions, has been used to assess the sensitivity of the impacts to parametric uncertainty and to perform capacity calculations [17].

The results of the groundwater assessment are then used in the assessment of safety during the Period of Authorisation [13] and in the non-human biota assessment [16]. Both use outputs from deterministic cases using best estimate values for cap infiltration. The infiltration rates are also used in the gas assessment [5] to consider ‘early’ onset of membrane degradation.

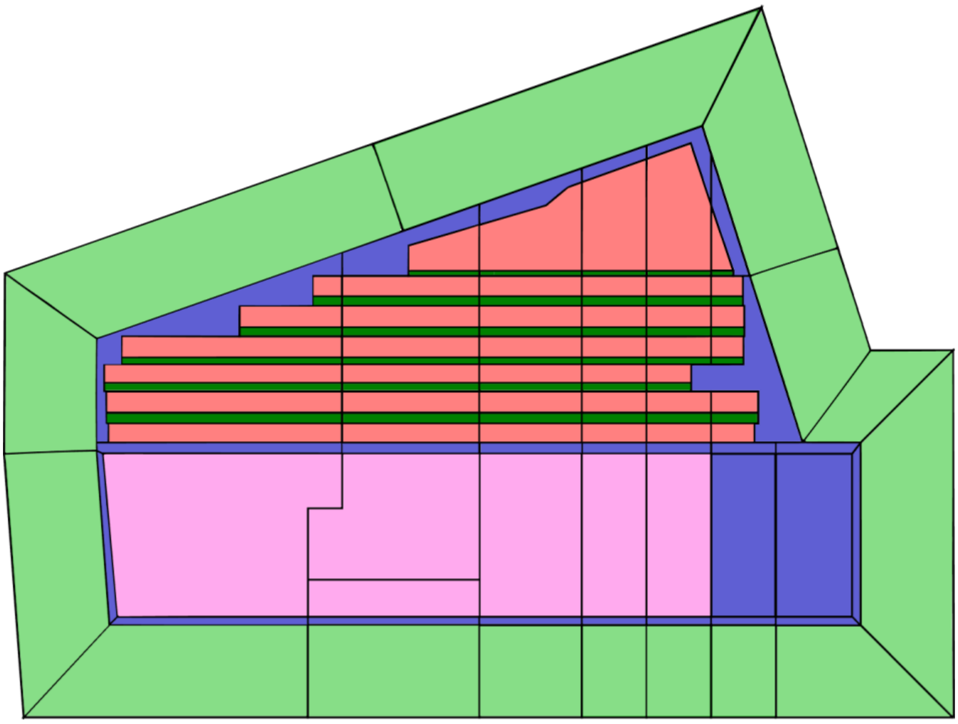


Figure 5.24: View of the Compartment Flow Model from above showing compartment stacks representing: trenches (brick red); vaults (pink); the geology between the trenches (dark green), the geology between vaults, trenches and cut-off wall (blue); and the external geology surrounding the repository (light green). Note that Vaults 13 and 14 are still demarcated in the mesh but are assigned the same materials as the surrounding geology [24].

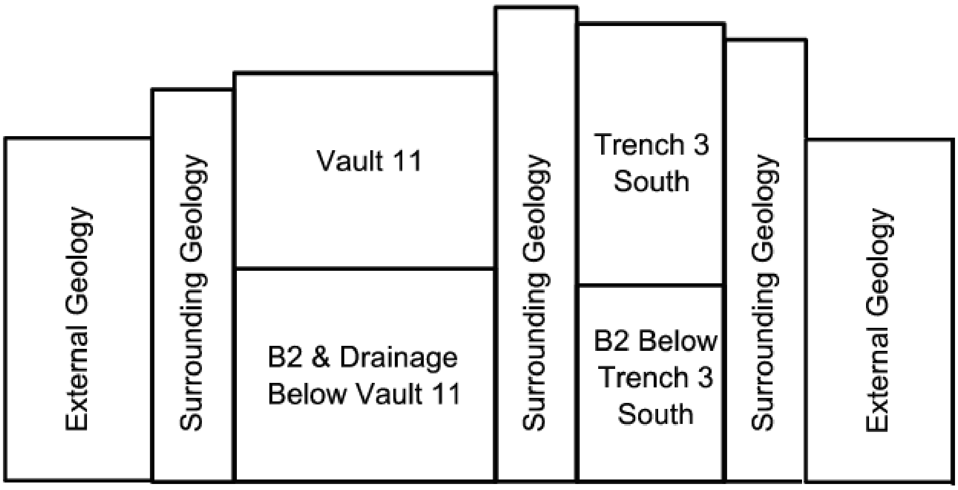


Figure 5.25: A schematic vertical west-east cross-section through the Compartment Flow Model at Vault 11. The External Geology compartments are outside the cut-off wall. The vertical dimensions are not to scale, and only Trench 3 has been included for clarity. Vaults and trenches have two compartments in each stack, elsewhere there is only one compartment per stack. Each compartment can have multiple material layers [24].

The CFM compartments, for the most part, map directly to an equivalent cell in the groundwater assessment model, allowing the CFM to be embedded directly within the GoldSim model, calculating the equilibrium flows and compartment water contents at each timepoint.

While the CFM is a simpler model, there are some situations where the CFM can more easily and realistically represent flows within the repository. This is particularly true for the representation of the largely desaturated conditions below the cap. While the ConnectFlow model and the CFM agree well when it comes to water levels within the repository, the finite-element model can struggle representing to represent water fluxes in highly unsaturated areas. Conversely, the CFM is explicitly designed to deal with these unsaturated situations and can more easily and realistically represent the flows. Consequently, the CFM is thought to predict more realistic flows in this situation.

Data from the ConnectFlow model are also used to define the CFM fixed-head boundary condition, applied at the bottom of the model (base of unit B2) to represent the Regional Groundwater head. The value of this head is calculated by averaging head values calculated in the hydrogeological model in the unit B3 layer under the repository. For the current-day model, this value could be obtained empirically from the current-day groundwater level as observed in boreholes, and indeed the hydraulic conductivities in the hydrogeological model are conditioned specifically in order to fit this measurement data. However, the predicted water levels from the ConnectFlow model are necessary for future times for which measured data are not available. For future models, the CFM uses the water levels from the snapshot ConnectFlow models, linearly interpolating for values between the snapshot model dates.

The domain of the CFM includes the repository and the surrounding hydrogeological unit B2. The groundwater assessment model extends further, including a representation of the B3 hydrogeological unit. To characterise flow within this unit, the B3 flow rates calculated in the ConnectFlow model are input into the groundwater assessment model. For the probabilistic simulations distributions of the B3 flow rates are applied using the standard deviations derived for the combined uncertainty studies described in Subsection 5.3.

6 Summary and Conclusions

This report fulfils the key objective to provide the relevant understanding of the geology and hydrogeology and demonstrate how this information has been used to represent groundwater flow and contaminant transport pathways within the ESC. The report provides a thorough and structured response to all the relevant requirements of both the GRA and GRR.

A comprehensive and proportionate approach to site investigation and characterisation has been implemented, as required by both the GRA and GRR. Our iterative programme has included both intrusive and non-intrusive investigation methods − such as boreholes, trial pits, CPTs, geophysics, LiDAR, and aerial photography − which has enabled us to progressively build knowledge of the site's geological and hydrogeological setting. Although there have been advances in the geological and hydrogeological understanding since the 2011 ESC, the basic stratigraphy has not changed. The site is still understood to consist of a complex sequence of Quaternary deposits (up to ~70 m thick) overlying Sherwood Sandstone Group bedrock.

A substantially revised and highly detailed three-dimensional (3-D) geological model has been developed through extensive integration, review and reinterpretation of multiple datasets. Significant effort has been invested in the iterative development of the stratigraphic framework, with repeated testing and refinement of geological interpretations to ensure consistency across site-scale and regional-scale representations. The revised model incorporates markedly improved spatial resolution and, for the first time, systematic integration of offshore geophysical datasets. This work has enabled explicit representation of geological features such as channel structures that were previously only inferred or simplistically assumed. The bedrock model has been comprehensively reworked to include greater detail on faulting and structural controls, and the weathering profile at the bedrock surface has been significantly improved through detailed reinterpretation.

We expect that future site investigation work will be required to support future vault developments and extension of the cut-off wall. This data will be incorporated into the geological model alongside general excavation data. The geological model will be maintained, throughout the operational period, and periodically reviewed to take into account any new developments in the geological understanding of the site and wider area.

The 3-D geological model provides the framework for hydrogeological modelling, allowing for better calibration, scenario analysis, and uncertainty quantification. Since 2011, we have incorporated a substantial amount of new hydrogeological data into our understanding and models. This includes data from additional boreholes, updated groundwater and surface water monitoring, and new hydrogeochemical analyses. The hydrogeological conceptual model has been reviewed; however, the core elements remain consistent with 2011 ESC. Groundwater flow is still understood to occur primarily within the Quaternary deposits and the upper part of the bedrock, down to depths of less than 100 m. It is divided into Upper and

Regional systems. The flow in the Upper Groundwater is predominantly downward through clay-rich deposits where it joins the Regional Groundwater. The overall direction of groundwater flow in the Regional system is from higher ground inland toward the coast, through sand and gravel deposits, driven by the hydraulic gradient between inland recharge and sea level (see Figure 4.17).

Combined with the 3-D geological model, the hydrogeological conceptual model has been used as a basis for the development of calibrated hydrogeological models that simulate current and future groundwater behaviour, contaminant pathways, and the impact of engineered features such as caps, cut-off walls, and vaults. The models account for the staged construction and degradation of these features, as well as future site evolution scenarios, including climate change, sea-level rise, and coastal erosion. This enables us to simulate how groundwater pathways and contaminant migration may change over time, and to demonstrate the resilience of the repository's engineering to foreseeable future changes over the next few thousand years. The hydrogeological models provide input data to the groundwater pathway assessment model.

We have undertaken work to assess the effects of hydrogeological uncertainties at the LLWR site, including in bulk permeabilities; heterogeneity; bedrock faulting; offshore and internal structure of the confining unit; near-surface and recharge variability; and saline intrusion. Whilst there are variations in flow paths associated with these uncertainties, we can demonstrate that the overall pattern of flow is unaffected and that the representation of the groundwater pathway in the safety assessment is robust.

The site characterisation data collected have also informed contaminated land risk assessment and the development of targeted remediation strategies, ensuring that risks to human health and the environment are properly identified and managed. The findings of the quantitative risk assessments identify that the risks from contaminated land at the LLWR are low given the current land use and management procedures that are applied. Remediation of some areas has already been undertaken and plans for further work are being developed.

In conclusion, the LLWR site is well characterised in terms of its geological and hydrogeological setting. The models developed provide a sound basis for safety assessments and facility performance evaluations and are supported by a comprehensive data collection and monitoring programme. The iterative approach to site investigation, model refinement, and uncertainty analysis ensures that the ESC remains fit for purpose as knowledge and site conditions evolve. There are no economically viable mineral resources in the immediate vicinity, and groundwater abstraction is limited, further supporting the suitability of the site for its intended purpose. The ongoing programme of data collection, monitoring, and model development will continue to inform future assessments and support safe management of the LLWR.

7 References

[1] Nuclear Waste Services, “2026 Environmental Safety Case for the LLWR: Main Report,” LLWR/ESC/R(26)10166, May 2026.

[2] Nuclear Waste Services, “2026 Environmental Safety Case for the LLWR: Management and Dialogue,” LLWR/ESC/R(26)10167, May 2026.

[3] Nuclear Waste Services, “2026 Environmental Safety Case for the LLWR: Site History and Description,” LLWR/ESC/R(26)10168, May 2026.

[4] Nuclear Waste Services, “2026 Environmental Safety Case for the LLWR: Disposal Facility Inventory,” LLWR/ESC/R(26)10169, May 2026.

[5] Nuclear Waste Services, “2026 Environmental Safety Case for the LLWR: Engineering Design,” LLWR/ESC/R(26)10170, May 2026.

[6] Nuclear Waste Services, “2026 Environmental Safety Case for the LLWR: Near Field,” LLWR/ESC/R(26)10171, May 2026.

[7] Nuclear Waste Services, “2026 Environmental Safety Case for the LLWR: Site Evolution,” LLWR/ESC/R(26)10173, May 2026.

[8] Nuclear Waste Services, “2026 Environmental Safety Case for the LLWR: Monitoring,” LLWR/ESC/R(26)10174, May 2026.

[9] Nuclear Waste Services, “2026 Environmental Safety Case for the LLWR: Optimisation and Site Development Plan,” LLWR/ESC/R(26)10175, May 2026.

[10] Nuclear Waste Services, “2026 Environmental Safety Case for the LLWR: Waste Management Plan,” LLWR/ESC/R(26)10176, May 2026.

[11] Nuclear Waste Services, “2026 Environmental Safety Case for the LLWR: Safety Functions,” LLWR/ESC/R(26)10177, May 2026.

[12] Nuclear Waste Services, “2026 Environmental Safety Case for the LLWR: Engineering Performance Assessment,” LLWR/ESC/R(26)10178, May 2026.

[13] Nuclear Waste Services, “2026 Environmental Safety Case for the LLWR: Environmental Safety During the Period of Authorisation,” LLWR/ESC/R(26)10179, May 2026.

[14] Nuclear Waste Services, “2026 Environmental Safety Case for the LLWR: Assessment of Long-term Radiological Impacts,” LLWR/ESC/R(26)10180, May 2026.

[15] Nuclear Waste Services, “2026 Environmental Safety Case for the LLWR: Hydrogeological Risk Assessment,” LLWR/ESC/R(26)10181, May 2026.

[16] Nuclear Waste Services, “2026 Environmental Safety Case for the LLWR: Assessment of Radiological Impacts on Non-human Biota,” LLWR/ESC/R(26)10182, May 2026.

[17] Nuclear Waste Services, “2026 Environmental Safety Case for the LLWR: Implementation,” LLWR/ESC/R(26)10183, May 2026.

[18] Nuclear Waste Services, “2026 Environmental Safety Case for the LLWR: Addressing Regulatory Requirements and Feedback,” LLWR/ESC/R(26)10184, May 2026.

[19] Environment Agency, Northern Ireland Environment Agency, Scottish Environment Protection Agency, “Near-surface Disposal Facilities on Land for Solid Radioactive Wastes: Guidance on Requirements for Authorisation,” February 2009.

[20] Scottish Environment Protection Agency, Environment Agency and Natural Resources Wales, “Management of Radioactive Waste from Decommissioning of Nuclear Sites: Guidance on Requirements for Release from Radioactive Substances Regulation,” Version 1.0, July 2018.

[21] Amentum, “LLWR Conceptual Geology Report,” DEPRWD14-17, Issue 0.1 (Pre-publication), March 2026.

[22] Amentum, “Geological Model for the LLWR,” DEPRWD14-20, Issue 1 (Pre-publication), 2026.

[23] Amentum, “Hydrogeological conceptual model for the LLWR,” DEPRWD14-15, Issue 1 (In preparation), October 2025.

[24] Amentum, “Hydrogeological model for the LLWR,” DEPRWD14-16, Issue 1 (Pre-publication), November 2025.

[25] Ministry of Supply, “History of ROF: Drigg,” SUPP5/956. MOS, 1945.

[26] British Nuclear Fuels Limited, “Drigg Post-closure Safety Case,” September 2002.

[27] British Nuclear Fuels Limited, “Drigg Post-closure Safety Case: Geological Interpretation,” September 2002.

[28] Environment Agency, “The Environment Agency’s Assessment of BNFL’s 2002 Environmental Safety Cases for the Low-level Radioactive Waste Repository at Drigg,” NWAT/Drigg/05/001, June 2005.

[29] Nexia Solutions, “Drigg Vaults Project: Interpretation of Phase I and II Site Investigation Data,” Report (06)6620, February 2006.

[30] URS Corporation, “Installation of Stage 6 (offsite) Boreholes Factual Report,” 49308240, October 2009.

[31] U. Michie, J. Hunter and G. Towler, “LLWR ESC: The Geology of the LLWR Site and Surrounding Region,” QRS-1443Y-R1 Version 2, October 2010.

[32] LLW Repository Ltd, “The 2011 Environmental Safety Case: Hydrogeology,” LLWR/ESC/R(11)10022, May 2011.

[33] Environment Agency, “Review of LLW Repository Ltd's 2011 Environmental Safety Case: Site Understanding,” Issue 1, May 2015.

[34] Nuclear Industry Radioactive Waste Executive, “The Quaternary Geology of the Sellafield Area. Nirex Report S/97/002,” 1997.

[35] Geological Consultants Ltd, for UK Nirex, “The Geology of the Drigg Site: 1996 Update,” Report No GEO/96/25, 1996.

[36] G. P. Eaton and G. D. Williams, “The Quaternary Geology of the Sellafield Area,” Nirex Report 519, 1996.

[37] Fugro, “Moorside Site Characterisation Programme: On- and Off-shore Works Report on Ground Investigation without Geotechnical Evaluation Report Part II: Offshore Works - Seabed and Geophysical Surveys,” Fugro Reference G151058U-REPII(04), September 2017.

[38] International Atomic Energy Agency, “Management of Site Investigations for Radioactive Waste Disposal Facilities,” IAEA Nuclear Energy Series ISSN 1995-7807 ; no NW-T-1.40, 2024.

[39] Amentum, “Uncertainty Quantification for the UK LLWR Hydrogeological Model,” Amentum Document no: DEPRWD14-14 Revision: Issue 1, May 2025.

[40] M. C. Akhurst, R. A. Chadwick, D. W. Holliday, M. McCormac, A. A. McMillan, D. Millward and B. Young, “Geology of the West Cumbria District. Memoir for the 1:50,000 Geological Sheets 28 Whitehaven, 37 Gosforth and 46 Bootle (England and Wales),” British Geological Survey, 1997.

[41] P. Stone, D. Millward and B. Young, “British Regional Geology: Northern England (fifth Edition),” *British Geological Survey,* 2010.

[42] G. M. Smith, H. S. Fearn, K. R. Smith, J. P. Davis and R. Klos, “Assessment of the Radiological Impact of Disposal of Solid Radioactive Waste at Drigg. NRPB-M148. NRPB,” Chilton, 1988.

[43] British Nuclear Fuels Limited, “Drigg Post Closure Safety Case: Hydrogeological Interpretation,” 2002.

[44] Nexia Solutions, “LLWR Lifetime Project: Review and Update of the 2002 Hydrogeological Conceptualisation,” Report 7743 Version 1.1, October 2006.

[45] R. Schaldach and J. A. Priess, “Integrated Models of the Land System: A Review of Modelling Approaches on the Regional to Global Scale,” *Living Reviews in Landscape Research,* vol. 2(1), pp. 1-34, 2008.

[46] D. A. Valters, “Modelling Geomorphic Systems: Landscape Evolution,” *In Geomorphological Techniques (British Society for Geomorphology),* 2016.

[47] D. Patel, M. Natali, E. M. Lidal, J. Parulek, E. V. Brazil and I. Viola, “Modeling Terrains and Subsurface Geology,” 2021.

[48] Nexia Solutions, “LLWR Lifetime Project: Reinterpretation of the Quaternary Geology of the LLWR Site and the Surrounding Region,” Report (07)8345, August 2007.

[49] Jacobs Clean Energy Ltd, “Task 1.3 Near Surface Disposal - Site Characterisation (Intrusive Investigations) Interpretive Report,” Jacobs Document No DEPRWD11-01. Rev. 1., 2022.

[50] C. McGhee, D. Muhammed, N. Simon, S. Acikalin, J. E. P. Utley, J. Griffiths, L. Wooldridge, I. T. E. Verhagen, C. van der Land and R. H. Worden, “Stratigraphy and Sedimentary Evolution of a Model Macro-tidal Incised Valley: An Analogue for Reservoir Facies and Architecture,” *Sedimentology,* vol. 69(2), pp. 696-723, 2021.

[51] Nexia Solutions, “LLWR Lifetime Project: Reinterpretation of the Quaternary Geology of the LLWR Site and the Surrounding Region: Regional and Site-scale 3D Geological Modelling,” Report (07)8509, May 2007.

[52] S. Birks, “Geological and Geomorphological Characterisation of West Cumbria,” Ph.D. Research Project, Department of Civil and Environmental Engineering (Geotechnics), Imperial College London, 2026.

[53] Jacobs Clean Energy Ltd, “Review of Historical Stream Positions at LLWR,” Jacobs Document No 209998/005. Issue 03, 2022.

[54] Fugro, “Technical Note on Evaluation of Drigg Beach Cliff and Surrounding Geomorphology,” G170017U_TN01, 2018.

[55] Jacobs Clean Energy Ltd, “Seascale Beach Cliff Technical Note,” Jacobs Document No DEPRWD06_02. Rev. 02, 2024.

[56] Environment Agency, “LIDAR Composite DTM 2020 - 1m,” 2025. [Online]. Available: https://www.data.gov.uk/dataset/b1ff0a9c-74d3-4b97-a3fb-c8ab39ef6152/lidar-composite-dtm-2020-1m. [Accessed 17 November 2025].

[57] Environment Agency, “Multibeam Bathymetry,” 2025. [Online]. Available: https://environment.data.gov.uk/dataset/5fa53736-11f5-417b-b160-9ac98bd012f5. [Accessed 17 November 2025].

[58] Geological Consultants Ltd, for UK Nirex, “Interpretation of the BNFL/Nirex Offshore High Resolution Seismic Data,” Report No GEO/95-17, 1996.

[59] J. W. Merritt and C. A. Auton, “An Outline of the Lithostratigraphy and Depositional History of Quaternary Deposits in the Sellafield District, West Cumbria,” *Proceedings of the Yorkshire Geological Society,* vol. 53(2), pp. 129-154, 2000.

[60] LLW Repository Ltd, “Site Characterisation Report,” RP/LLWR/PROJ/00192, March 2015.

[61] Nuclear Waste Services, “LLWR Site Characterisation Report,” RP-3409334.05-ENV-00042, October 2022.

[62] Nuclear Waste Services, “Management and Control of Asbestos,” NWSSOP 47.04, Issue 0, November 2025.

[63] Nuclear Waste Services, “Preparation for Excavations,” NWSSOP 56.05, Issue 1, February 2026.

[64] Nuclear Waste Services, “Safe Management of Land Contamination,” NWSSOP 02.06.01, Issue 1, February 2026.

[65] Ministry of Supply, “Royal Ordnance Factory, Typescript history of ROF Drigg,” YDX 521/2. MOS, 2000.

[66] LLW Repository Ltd, “LLWR Site End State. Gate B: Preferred Options and Assumptions,” LLWR/ESC/R(22)10132, January 2022.

[67] Nuclear Waste Services, “Control of Excavation Activities (Permit to Dig),” NWSSOP 56.05_01, Issue 1, February 2026.

[68] British Nuclear Fuels Limited, “Mineral and Water Resource Potential at Drigg, DTP/146,” 2003.

[69] Halcrow Group Ltd, “Review of Historical and Future Potential Coastal Change at Drigg, Cumbria,” Halcrow report DECA/ TGM2002/1 for BNFL, 2003.

[70] J. H. Powell, C. N. Waters, D. Millward and N. S. Robins, “Managing Radioactive Waste Safely: Initial Geological Unsuitability Screening of West Cumbria,” British Geological Survey Research Report.

[71] British Geological Survey, “National Geological Screening: Northern England - Minerals and Waste Programme,” Commissioned Report CR/17/097, 2018.

[72] Jacobs, “SSSI Water Level Review,” Report No 209851/004, Issue 2, August 2020.

[73] Nexia Solutions, “LLWR Lifetime Project: Reassessment of the LLWR Site Water Balance,” Report No (07) 8507, 2007.

[74] Nexia Solutions, “LLWR Lifetime Project: Estimation of LLWR Stream Baseflows and Implications for Water Balance and Recharge,” Report (08)9768, Issue 1, July 2009.

[75] Serco Group plc, “Hydrogeological Modelling for LLWR 2011 ESC,” SERCO/TCS/E003632/007 Issue 3, April 2011.

[76] Amec, “An Analysis of the Trench Cap Performance,” Amec Doc Ref 201372/02, August 2014.

[77] Nuclear Waste Services, “2023 Interim Trench Cap and Cut-off Wall Performance Review,” RP-3409334.05-ENV-00165, May 2024.

[78] Nuclear Waste Services, “2024 Disposal Area Performance Report,” RP-3409334.05-ENV-00240, May 2025.

[79] Nuclear Waste Services, “LLWR 2026 ESC: Engineering Performance Assessment. Vaults and Trenches,” QRS-1895C-PR2, Version 1.6, October 2024.

[80] S. Burne, H. S. Wheater and A. P. Butler, “Program User Guide for WATBAL,” Version 2.0, ICON Limited report CI 141, 1999.

[81] N. Thompson, I. A. Barrie and M. Ayles, “The Meteorological Office rainfall and evaporation calculation system: MORECS,” Hydrological Memorandum No 45, London, 1981.

[82] Jacobs, “Review of hydrogeological inputs,” Jacobs Document No DEPRWD14/013, July 2024.

[83] Environment Agency, “Flood Map for Planning,” 2025. [Online]. Available: https://flood-map-for-planning.service.gov.uk. [Accessed 26 November 2025].

[84] Nuclear Waste Services, “2024-25 Environmental Monitoring Summary Report,” RP-3409334.05-ENV-00241, September 2025.

[85] Entec UK Ltd, “ESC Hydrogeological (Slug) Testing,” Report 26213 Issue 2, November 2009.

[86] Serco Group plc, “Examination of the Possible Relationship Between Hydraulic Conductivity and Lithology for the Quaternary at LLWR,” SERCO/TAS/003270/001, Issue 4, July 2010.

[87] Nexia Solutions, “The Proposed Use of Tracer Testing to Improve Understanding of the Hydrogeology of the Low Level Waste Repository,” Nexia report (07) 8742, Issue 2, September 2007.

[88] Amec, “Integration of Geology and Hydrogeology at the LLWR Site,” Report D005864/002, Issue 2, 2012.

[89] C. P. Jackson and S. P. Watson, “Nirex 97: An Assessment of the Post-closure Performance of a Deep Waste Repository at Sellafield, Volume 2: Hydrogeological

Conceptual Model Development - Effective Parameters and Calibration," Nirex Science report S/97/012, 1997.

[90] British Nuclear Fuels Limited, "Drigg Post-closure Safety Case: Far-field Geochemical Interpretation," September 2002.

[91] Entec UK Ltd, "A Report on Hydrogeochemistry of Non-radioactive Contaminants in LLWR Leachate and Groundwater," Entec report 27634, December 2010.

[92] Amec Foster Wheeler, "Review and Suggestions to Enhance Geochemical Understanding of the Far Field at LLWR," 2017.

[93] Jacobs, "Update of the hydrogeochemical interpretation of the LLWR site," Ref: 209360 001, September 2020.

[94] LLW Repository Ltd, "Assessment of the Applicability of Radiological LLWRAS for Comparison Against Environmental Monitoring Data," LLWR/MON/Mem(19)003, June 2020.

[95] LLW Repository Ltd, "Hydrogeological Risk Assessment for the LLWR," LLWR/ESC/R(17)10090, Issue 2, March 2018.

[96] Nuclear Waste Services, "2026 Review of environmental baselines and LLWRAS," LLWR/MON/Mem(26)001, March 2026.

[97] International Organization for Standardization, "Determination of the characteristic limits (decision threshold, detection limit and limits of the coverage interval) for measurements of ionizing radiation — Fundamentals and applications — Part 2: Fundamentals and general applications," ISO 11929 2:2019, Geneva, 2019.

[98] Serco Group plc, "Hydrogeological Conceptual Model for the LLWR 2011 ESC," SERCO/TCS/E003632/008 Issue 2, April 2011.

[99] Quintessa, "LLWR 2026 ESC: Engineering Performance Assessment. Vaults and Trenches," QRS-1895C-PR2 Version 1.6, October 2024.

[100] Amec Foster Wheeler, "Assessing Aspects of Near-field Heterogeneity for the LLWR," CRM 79246, 2019.

[101] G. M. Williams, A. F. Pitty, C. Balch, F. Graham and T. J. Sumerling, "Geomorphological Processes and Landforms at Drigg, Cumbria, 1989. The Development and Specification of Scenarios for Post-closure Radiological Safety

Assessment of the Drigg LLW Disposal Site, Prepared for BNFL," Intera-ECL Report 1931-9, 1989.

[102] Department for Environment, Food and Rural Affairs, "Magic Map – Aquifer Designations Layer," 2025. [Online]. Available: https://magic.defra.gov.uk. [Accessed 26 November 2025].

[103] Environment Agency, "Catchment Data Explorer West Cumbria Permo-Triassic Sandstone Aquifers Water Body," 2025. [Online]. Available: https://environment.data.gov.uk/catchment-planning/WaterBody/GB41201G102000. [Accessed 26 November 2025].

[104] Jacobs, "Drigg Deep Borehole – Water Features Survey," DEPRWD14, July 2023.

[105] Cumberland Council, *FOI 14194 – Reply,* by e-mail, 26 May 2023.

[106] R. Brassington, "Review of Potential Groundwater Abstraction at the LLWR Facility Drigg West Cumbria," Rick Brassington Report 1548, May 2010.

[107] Nuclear Waste Services, "Data for Water Abstraction Wells," LLWR/ESC/Mem(23)452, 28 August 2025.

[108] Jacobs, "Drigg Deep Borehole Abstraction," DEPRWD14 2.12, Issue 1, January 2024.

[109] Amec Foster Wheeler, "Revised Assessment Model for the Groundwater Pathway," Report 205547/001 Issue 5, 2019.

[110] Amentum, "ConnectFlow v13.1: Technical summary," 2025. [Online]. Available: https://www.connectflow.com/resources/docs/conflow_technical.pdf. [Accessed 19 October 2025].

[111] Amec Foster Wheeler, "The Effect of Faults on the Hydrogeology at the LLWR," Amec Report D005864/003, Issue 1, August 2012.

[112] Watermark Numerical Computing, "Model-Independent Parameter Estimation User Manual Part 1: PEST, SENSAN and Global Optimisers," 6th Edition, 2016.

[113] Serco Group plc, "Radiological Assessment Calculations for the Groundwater Pathway for the LLWR 2011 ESC," SERCO/TCS/E003796/011, Issue 6, April 2011.

[114] Serco Group plc, "Non-Radiological Assessment Calculations for the LLWR 2011 ESC," TAS/003796/012, Issue 5, April 2011.

[115] Jacobs, “Lot 3 Hydro Uncertainties 2020: Addressing Geological and Hydrogeological Uncertainty,” Report no 209998/004, Issue 2, February 2022.

[116] Nexia Solutions, “LLWR Lifetime Project: v0 Saline Model,” Report (07)8506, 1 August 2008.

[117] Jacobs, “Effect of Coastal Erosion on the Risks from Well Water,” Report no DEPRWD37-TLN-002, Issue 4, August 2024.

[118] Quintessa, “Climate Projections for the 2026 ESC: Analysis and Supporting Information,” QRS-10128A-1-NAM, Version 2.0, December 2023.

[119] Amentum, “Infiltration Through the Final Cap,” DEPRWD14/10, 21 October 2024.

[120] Serco Group plc, “Elicitation of Uncertainties for LLWR,” Serco/E.003796/010, April 2011.

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