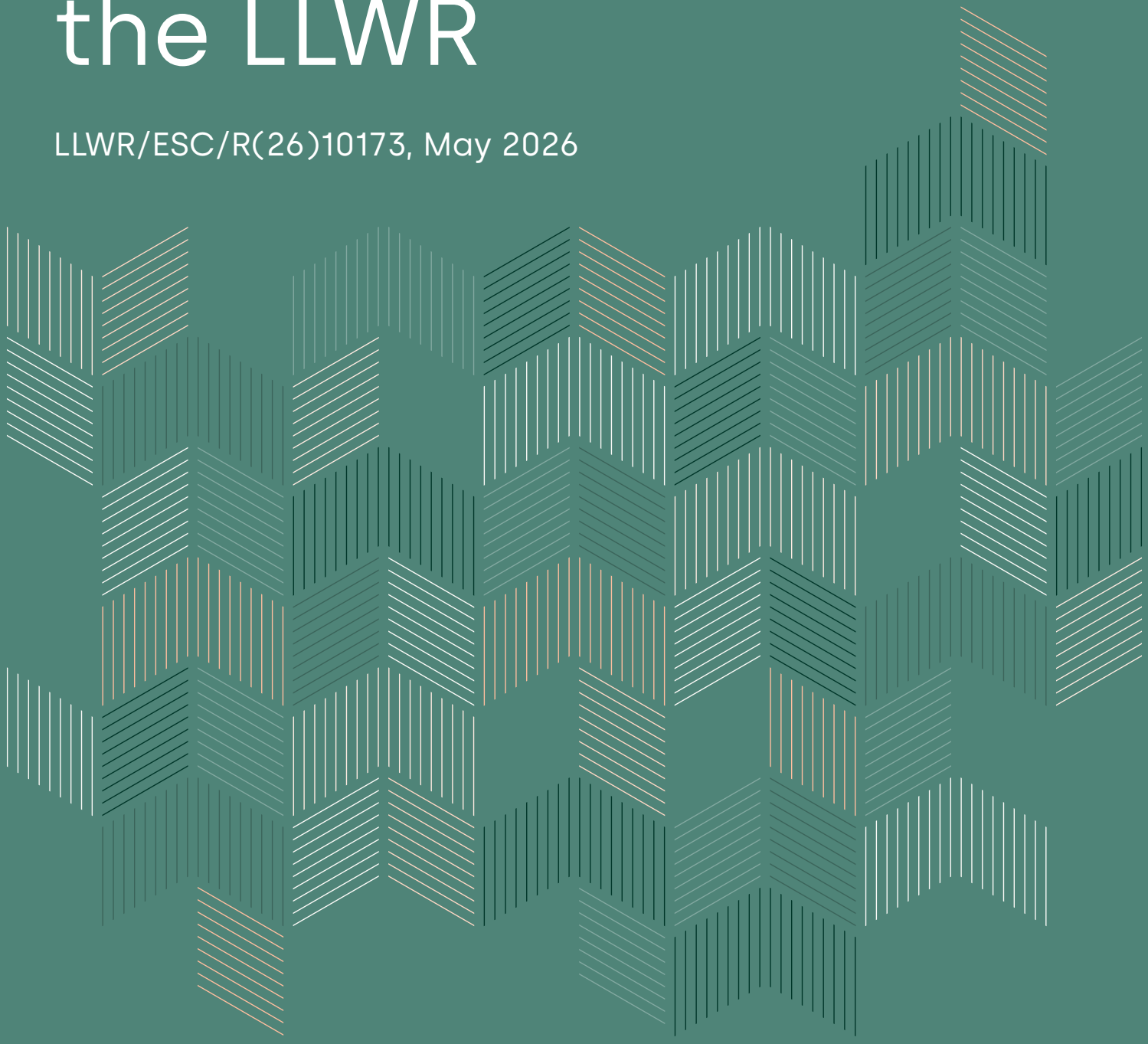
Nuclear Waste Services

SITE EVOLUTION

2026 Environmental Safety Case for the LLWR

LLWR/ESC/R(26)10173, 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.

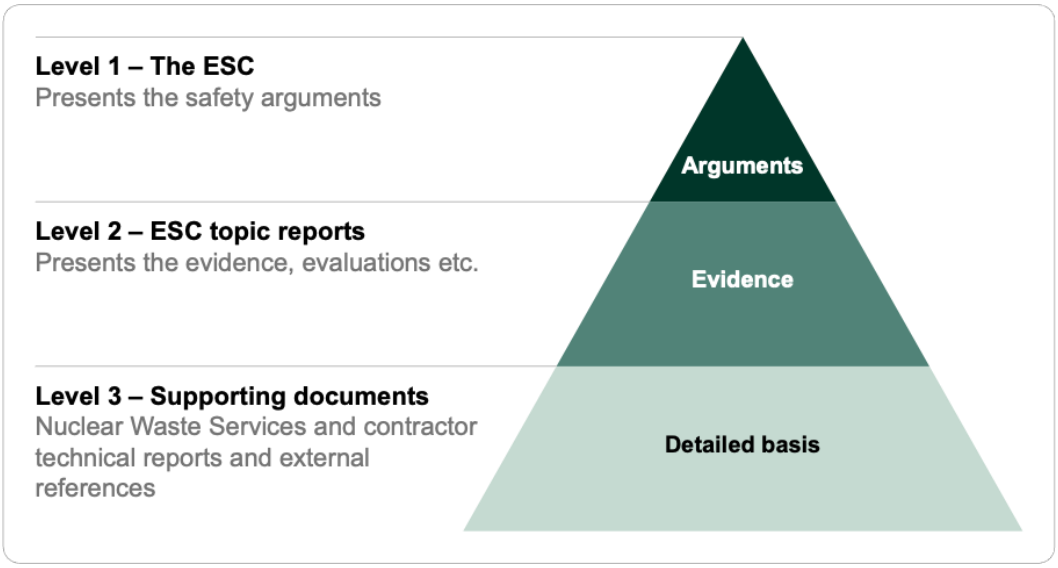
The 2026 ESC is issued under the authority of the Nuclear Waste Services' Executive Director of Sites and Operations.

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.

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



Level 1	
Main Report [1]	
Level 2	
Management and dialogue	
Management and Dialogue [2]	Describes our environmental management systems and interactions with regulators and stakeholders
System characterisation and understanding	
Site History and Description [3]	Provides a history and description of the site
Disposal Facility Inventory [4]	Describes the wastes already disposed and wastes that may be disposed at the facility

Engineering Design [5]	Presents the engineering design of the current facility and proposed changes as further disposal vaults are built and the disposal facility is closed
Near Field [6]	Describes our understanding of the chemical and physical evolution of the engineered disposal system
Hydrogeology [7]	Describes our understanding of the geology and hydrogeology of the site
Site Evolution (this report)	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

A fundamental component of the environmental safety case for any radioactive waste disposal facility is a demonstration of an understanding of the future evolution of the site, its environmental setting, and related uncertainties, all based on sound science. This provides important input to estimating the future performance of the facility and the site. This document presents the understanding of processes that are important to site evolution and summarises the underpinning evidence.

The Low Level Waste Repository (LLWR) is situated near to the Cumbrian coastline. Historical maps indicate that the coast has eroded. Given this observation, and an anticipated rise in sea level that would increase rates of erosion, we expect that at some point in the future the site will be disrupted by coastal erosion. We have undertaken a programme of work, including expert workshops and review, to improve understanding of coastal erosion. This topic is the focus of this report.

The report also addresses the broader implications of climate change to provide a clear basis for representing future changes at the site and its environment in quantitative assessments of performance. Key effects include infiltration through the engineered cap, hydrogeological conditions, land use and human habits, and ecological characteristics. These influences are complex and in some cases competing; for example, more rapid coastal erosion can increase impacts in the coastal erosion pathway by reducing the time available for radioactive decay, while simultaneously reducing impacts via the groundwater pathway by limiting opportunities for well intrusion. Given these interactions, no single climate scenario can be identified as uniformly cautious across all pathways, and the ESC therefore considers a range of scenarios to ensure robust and balanced safety arguments.

Climate and Sea-level Projections

Three emissions scenarios – Reference, Low, and High – are used to capture the range of possible future greenhouse gas pathways. Climate and sea-level projections at the LLWR site are based on downscaled global models and local meteorological data using these scenarios as the basis.

- Reference Emissions Scenario: CO_2 emissions remain at current levels until mid-century before declining.[2]
- Low Emissions Scenario: CO_2 emissions decline rapidly, reaching net zero after 2050, followed by net negative emissions.

[2] For the Period of Authorisation, we adopt the High Emissions Scenario as the central case in our assessments, reflecting regulatory advice.

- High Emissions Scenario: CO_2 emissions roughly double by 2050, peaking around 2090, with high atmospheric concentrations persisting.

Projected Temperature and Precipitation Changes

Under the Reference emissions scenario, mean annual temperature at the LLWR site is projected to peak at +2.4 °C above 1981 to 2010 values around 300 years after present (AP), returning to +0.5 °C by 10,000 years AP. In the Low Emissions Scenario, peak warming is limited to +1°C at 100 years AP before declining to +0.1 °C by 10,000 years AP. For the High Emissions Scenario, warming is most pronounced, with temperatures reaching a maximum of +7.4 °C at 300 years AP and remaining elevated at +2.6 °C at 10,000 years AP.

The climate maintains a general classification of 'temperate oceanic' under both the Reference and Low Emissions Scenarios, reflecting a biosphere similar to that of the present day. Under the High Emissions Scenario, the climate transitions to a 'humid subtropical' classification for a period, similar to present-day Portugal.

Higher emissions scenarios project more intense warming and wetter winters, with drier summers.

Sea-level Rise Projections

Relative sea-level rise (accounting for changes in both water and land levels) at the LLWR site is projected to reach 10 m (Reference), 23.3 m (High), or 0.7 m (Low) above present by 10,000 years AP.

These projections are derived from models that integrate both global and local factors influencing sea level. Global eustatic changes, such as thermal expansion of ocean water due to increased temperatures and the melting of polar ice sheets, are combined with the effects of small but ongoing local isostatic adjustments following retreat of ice sheets around 18,000 years ago.

Coastal Evolution and Site Disruption

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 our understanding of the coastal system and quantitative modelling studies, we have concluded that the disposal vaults will begin to be eroded on a timescale of several hundred to a few thousand years.

We have deployed several complementary models to forecast the rates and mechanisms of coastal erosion and to estimate the timing of repository site disruption at the LLWR facility. These approaches include the use of both empirical and process-based tools such as the

Coastal Recession Model (CRM) and the Soft Cliff and Platform Erosion (SCAPE) model, which are further supported by monitoring and analysis of historical shoreline movement, a detailed understanding of the coastal conceptual model and the application of straightforward extrapolations informed by historical records of coastal change and contemporary monitoring.

It is not considered feasible to guarantee protection from erosion over many hundreds to a thousand years using engineered structures. We make no provision for coastal defences and cautiously assume no future organisation would construct them. This position is consistent with regulatory guidance, which requires the repository to be passively safe without ongoing management and maintenance, including provision of coastal defences.

The principal processes leading to repository disruption are anticipated to include progressive undercutting of coastal cliffs, direct wave attack on exposed engineered structures, and, particularly under the High Emissions Scenario, episodic or sustained inundation due to rising sea levels. These mechanisms, acting in combination with ongoing coastal retreat, will ultimately result in the gradual exposure, fragmentation, and dispersal of repository materials into the adjacent coastal environment.

Waste and Engineered Material Behaviour

At the time of disruption, waste containers and engineered barriers will have undergone partial degradation, affecting their resistance to further erosion and dispersal.

The beach adjacent to the eroding repository will include sand, gravel, concrete fragments, and potentially resilient waste items, depending on the scenario and rate of erosion.

Analogues and monitoring have informed our understanding of how engineered and waste materials will fragment and disperse in the coastal system.

At the time of initial disruption, waste containers and engineered barriers within the repository will have already experienced varying degrees of physical and chemical degradation. This degradation could diminish their structural integrity, influencing both their ability to resist further coastal erosion and the likelihood of waste material release and dispersal.

As erosion progresses through the vaults, the beach environment will evolve. It is expected to consist of a mix of natural and waste materials, including sand, gravel, eroded concrete fragments from the repository structures, and possibly residual waste items that prove more resistant to weathering and transport. These materials will interact with tidal and storm-driven processes, affecting their distribution along the coastal zone and potentially further afield.

Our understanding of how engineered barriers and waste forms fragment, degrade, and move within a dynamic coastal system has been informed by observations of sites where similar materials have been released into coastal environments.

Uncertainties and Management

The projections carry significant uncertainty due to:

- future greenhouse gas emissions, global and regional climate responses, and ice-sheet behaviour;
- complex interactions between coastal geomorphology, sediment supply, and storm impacts;
- long-term modelling limitations and the extrapolation of historical rates to future, unprecedented conditions.

Therefore, the outcomes of the projections need to be treated with caution. While the analyses confirm that it is almost certain that the LLWR will be disrupted by coastal erosion at some point post closure, the timescales are best expressed within broad ranges.

To manage these uncertainties, we have considered three plausible scenarios that represent an appropriate range without assigning probabilities to any single outcome, and will consider the plausible range throughout the ESC. Our thorough understanding of the coastal conceptual model allows us to apply expert judgement to integrate evidence from the complimentary models and data sources, arriving at robust conclusions.

We continue to reduce relevant uncertainties through ongoing coastal monitoring, which will become more valuable as climate change and site evolution become more apparent in the coming decades. We have also included several research and development activities related to this area in the ESC forward plan.

Table of Contents

1 Introduction

1.1 Objectives

This report provides an overview of the underpinning characterisation and current understanding of the future natural evolution of climate and landscape in the vicinity of the LLWR. It summarises information and analyses concerning the expected effects of global climate change, and associated regional and local climate change, sea-level rise, coastal erosion and landscape evolution. The focus is on natural processes that could lead to disruption of the facility, primarily coastal erosion. Climatic changes that could affect the biosphere characteristics and the hydrological and hydrogeological regime are also addressed.

We have defined a conceptual overview of the site's projected evolution, supplemented by an assessment of relevant uncertainties shown as appropriate ranges. We also evaluated significant uncertainties and how they affect our projections.

As well as providing a clear basis for representing future changes at the site and its environment in quantitative assessments of performance, the report also has the objective of demonstrating that the understanding of the site and its development is based on sound scientific understanding and analysis. In particular, the understanding of the site evolution and related uncertainties must be sufficiently robust to underpin our general claims for the future evolution of the site and its environs, for example, in relation to the timescales for erosion of the site. Projections made and uncertainty ranges identified need to be sufficiently defined to underpin the models used for performance assessment calculations.

Box 1 identifies primary Requirements and supporting guidance or conditions, as given in the GRA [19], to which the subject matter of this report is especially relevant, and the information in this report is intended to satisfy or illustrate.

The 2026 ESC also considers impacts from the wider LLWR site, as part of its scope as a site-wide environmental safety case (SWESC). Although the focus of this report is on the disposal facility and satisfying the GRA, consideration of site evolution may be relevant to the evaluation of impacts to other wastes on site, considered in the Waste Management Plan [10].

Box 1: GRA Requirements most relevant to this report

Requirement R11: Site investigation. 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.

R11 represents the primary source of requirements relevant to this report. A range of other detailed requirements are also relevant, including (for example) the following.

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;
- development of the environmental baseline prior to facility construction;
- where relevant, consideration of the need to include a phase of underground investigation within the body of the host rock for the proposed disposal facility.

7.2.1(a): The environmental safety case should demonstrate a clear understanding of the disposal facility in its geological setting ('the disposal system') as it evolves.

7.3.29: As far as possible, use standard approaches to establish the environmental safety case, thus relying on appropriate expert judgement in gathering and interpreting evidence and applying it to construct and use the qualitative and quantitative models.

7.3.32: Take into account the potential for climate change. There is considerable uncertainty regarding the rate, amount and even the direction of possible climate change over different timescales, so consider a range of possibilities. The potential consequences of climate change include changes in rainfall patterns (which can affect watercourses and aquifers), changes in sea level, increased rates of erosion including coastal erosion, glacial cycling and glaciotectonic movements.

1.2 Scope

For any surface disposal facility, on a timescale of thousands (or at most tens of thousands) of years, it is likely that the facility will be damaged and ultimately destroyed by human actions,

natural processes or a combination of both, with attendant dispersal of the waste.[3] Current evidence as presented in this report leads to the conclusion that disruption and dispersion by coastal erosion is the likely fate of the LLWR.

Understanding how and when this may occur requires a range of processes to be investigated. The focus of this report is on:

- climate changes, including the influence of greenhouse gas emissions. This dictates the future change in sea level that is a critical factor in understanding the possible rate of coastal recession;
- geomorphological processes operating offshore, at the coast and on land. Taken together with sea-level rise this will determine the likely timing and character of the site's disruption.

Future human actions that could directly influence the repository or its environs are outside the scope of the report.[4]

Coastal defences are not part of the optimised Site Development Plan (SDP) for the LLWR, due to the rationale presented in the '*Optimisation and Site Development Plan*' [9] (see also Subsection 4.3.9).

Potential changes in climate that affect the local land use and water resources are also important to consider and are addressed in this report. The influence of climate change on hydrological and hydrogeological conceptual models is described in '*Hydrogeology*' [7], taking account of the climate evolution projections presented in this report.

We have undertaken a substantial programme of work to build an understanding of climate and landform changes that may affect the LLWR site. This work has been ongoing since the late 1990s, with several iterations of characterisation, analysis, synthesis and assessment. This report presents an integrated statement of the conclusions of the work, with references to the detailed analyses that have led to these conclusions.

The understanding presented in this report is required to underpin a range of arguments and analyses presented in other ESC reports, as outlined in Subsection 2.4.

1.3 Structure

The report is structured as follows.

- The background and context of the report are described in Section 2.

[3] For this reason, radioactive wastes that may be disposed of in a surface disposal facility are limited by environmental safety considerations.

[4] These are discussed in the 'Assessment of Long-term Radiological Impacts' report.

- Section 3 concerns the projections for global climate change and how they will affect the sea-level and inland landscape in West Cumbria.
- Section 4 presents the understanding of the processes that can cause the coastline to change and how they may be influenced by sea level change, resulting in projections of future coastal landscape change in the vicinity of the LLWR site.
- A summary of the projections for coastal and inland landscape changes is presented in Section 5.

A general glossary for the ESC is appended to the *'Main Report'* [1].

2 Background and Context

2.1 General Background

For context, a brief description of the LLWR site and its environs is provided below. A more detailed description of the site as it exists today and how it will be developed up to its closure is given in the '*Site History and Description'* report [3].

The use of the LLWR site dates to 1940, when the site was developed as a Royal Ordnance Factory. Disposal of LLW has taken place at the site since 1959, initially in a series of trenches and subsequently in concrete vaults. The LLWR receives waste from a range of consignors, including nuclear power stations, fuel cycle facilities, defence establishments, general industry, isotope manufacture sites, hospitals, universities and from the clean-up of historically contaminated sites.

The LLWR is located on the West Cumbrian coastal plain, about 0.5 km inland, to the west of the B5344 Seascale to Holmrook road, close to the village of Drigg and approximately 5 km south-east of the Sellafield nuclear site. The fells of the Lake District are located to the east. The Isle of Man is located due west of the facility, and the local and regional characteristics of the Irish Sea are also influenced by the Dumfries and Galloway coastline to the north, the north Wales coastline to the south, and the coast of Ireland further west. Features of the coastline include St Bees Head, the estuary complex comprising the rivers Irt, Mite and Esk that discharges to the sea opposite the village of Ravenglass, and the more distant Morecambe Bay. This regional and local context is set out in Figure 2.1. Figure 2.2 is an aerial photograph of the site from the south showing the key features and the proximity of the site to the coast.

The topography surrounding the site varies from about 25 m above current sea level (relative to Ordnance Datum, OD) to the north-east and west of the site to less than 5 m OD at the south-eastern site boundary. The existing and planned vault bases have elevations of 10 to 14 m OD, and final waste stack heights will be from 21 m OD (four-high container stacking) to up to 27 m OD (eight-high stacking). The trench bases have elevations of around 10 m OD. To the west of the site, the topography gently undulates towards a low cliff line marking the edge of the Drigg beach.

Apart from the nearby Sellafield nuclear site, the area is predominantly rural. The site is mainly surrounded by grazing land, but some cereal crops are grown in fields to the east. The area between the site and the coast is designated as a Site of Special Scientific Interest (SSSI), known as the Drigg Coast SSSI. The western boundary of the area of the site currently used for waste disposal and storage borders the SSSI. The Drigg Coast SSSI is also a Special Area of Conservation (SAC), and the coastline near the site is designated as a Marine Conservation Zone (MCZ), known as the Cumbria Coast MCZ.

Figure 2.1: Location of the LLWR site

Figure 2.2: Aerial photograph of the LLWR

The Drigg Stream flows through the site roughly parallel with the western site boundary. Towards the centre of the site, the Drigg Stream is joined by the East-West Stream, which originates off site to the north-east, draining farmland and taking water from the railway drain. The Drigg Stream leaves the site to the south and discharges into the River Irt, which is tidal at that point.

Previous studies have identified that, due to its coastal location, coastal erosion is an important issue for the environmental safety of the LLWR. The 2011 ESC and subsequent studies presented a comprehensive evaluation of the timing, nature and impacts associated with coastal erosion of the site, based on several decades of site investigations and detailed quantitative modelling. It concluded that the disposal vaults will begin to be eroded on a timescale of a few hundred to a few thousand years, with erosion of the vaults and trenches being complete within one to a few thousands of years. It also concluded that the associated radiological impacts would be consistent with regulatory guidance levels. The ESC also derived controls on the activity concentration and type of waste in future disposals to ensure impacts would remain optimised and consistent with regulatory guidance levels. The overall conclusions were accepted by the Environment Agency, who issued a permit for disposal of radioactive waste at the LLWR in 2015 [20].

2.2 Brief History of Relevant Studies

The collection of data and development of understanding regarding the evolution of the west Cumbrian coast in the vicinity of the LLWR (in the past and projections for the future) has been cumulative and iterative.

Analysis of historical coastal erosion rates and sea-level rise projections were undertaken in support of the 2002 Post Closure Safety Case (PCSC) [21], including identification of future climate and landscape change scenarios. The outcomes of the studies prepared for the 2002 submission and feedback from the Environment Agency review and subsequent liaison activities were then used to inform the development of the 'coastal studies forward programme' between 2002 and 2011. This centred on understanding and projecting the evolution of the West Cumbrian coastline over timescales of hundreds to thousands of years. The programme included the characterisation of past and present coastal conditions, climate and sea-level change reviews, and investigations into the area's geomorphology and hydrodynamics. These efforts were further supported by geophysical surveys, LiDAR surveys, aerial photography and analysis of historical maps and photography. Workshops with independent experts helped refine conceptual models and ensured that scenarios used for safety assessments were robust and scientifically sound.

A wide range of studies has addressed climate evolution, coastal characterisation, and the development of predictive models for coastal change and cliff recession. The results of these studies feed into an integrated understanding of how the coastline and site may develop. The programme's findings formed the foundation for both the 2011 ESC and ongoing future assessments.

Since the 2011 ESC, the focus of the ESC development programme in this topic area has been to reduce key uncertainties and maintain the ESC in alignment with current scientific consensus. This has involved:

- developing and using our understanding of site evolution to inform the ongoing optimisation of the engineering design [22];
- updating our climate projections to align with current scientific consensus, including the considerations of the Intergovernmental Panel on Climate Change (IPCC) and improvements to longer term and localised climate modelling [23];
- undertaking an annual coastal monitoring programme to further inform and underpin our coastal conceptual model and coastal evolution projections [24];
- subsequently updating our projections of coastal evolution, taking account of all of the above, plus updated modelling techniques and parameterisation [25].

2.3 Comments from Regulators on Previous Submissions

In its review of the site authorisation that was informed by (but not limited to) review of the 2002 PCSC [26], the Environment Agency recognised the considerable uncertainties in the emerging scientific understanding, and commented that:

> *'There is significant ongoing work in the area of climate change impacts…BNFL should keep abreast of developments in this area and update the safety case accordingly.'*

Requirement 2 of Schedule 9 (R2S9) of the resulting site Authorisation called for a review of risks arising from potential site termination events (including coastal erosion) and options for reducing them. In our 2008 submission against R2S9, calculations of radiological impact arising from coastal erosion were presented [27] based on schematic illustrations of possible coastal development [28]. In its review of the R2S9 submission, the Environment Agency commented [29]:

> *'We…conclude that the ESC can reasonably be based on the assumption that the LLWR is likely to be destroyed by erosion within several thousand years…This being the case, we expect the assessment of the impacts associated with the erosion of the facility to be appropriate for the 'normal' or expected evolution of the site…Given the fundamental shift to an assumption that the facility will be eroded within a few thousand years…we will expect LLW Repository Ltd to provide a more carefully justified and robust assessment of the exposures that could arise when that erosion takes place'.*

Subsequent liaison with the Environment Agency on these topics informed the approach to understanding coastal processes and their significance for the LLWR. In particular, in reference [30] the Environment Agency stated that:

> *'Provided that the specific requirements within the GRA are met, including ensuring that radiation dose constraints and risk targets to the public both during the operational and post closure periods are met; and the risks presented by the site are optimised; and where the site is under operational management, all necessary measures are taken to contain wastes; the potential for disruption by coastal erosion at some point in the future is an acceptable risk.'*

The Environment Agency undertook a comprehensive review of Site Evolution aspects during its review of the 2011 ESC [31]. In supporting the review, we responded to five formal Technical Queries on this topic area. The review concluded the following:

> *'We consider that the company has carried out a comprehensive assessment of the potential evolution of the LLWR. It has identified the main factors*

controlling the timing and nature of site disruption by coastal erosion and considered a sufficient and credible range of potential repository disruption scenarios. Significant uncertainty around future climate change and coastal evolution remains; however, the company has appropriately taken account of this by identifying and assessing the consequences of a reasonable range of disruption mechanisms and timescales. LLW Repository Ltd concludes that, irrespective of any future sea level rise, there is a low probability that the repository will remain intact for a period in excess of a few 1000 years from now. We agree that these projections are reasonable and represent best available knowledge at this time.

LLW Repository Ltd's conceptualisation of the evolution of the Drigg coastline and resultant disruption of the LLWR has provided an important input to safety arguments in the 2011 ESC and informed the safety assessment calculations. We are satisfied that the resulting assessments are realistic and adequately take account of uncertainties. We will require the company to maintain an ongoing forward programme of coastal evolution monitoring and to keep up to date with the latest research on long-term climate change.'

As part of this review, the Environment Agency raised fourteen Recommendations for consideration and two Forward Issues for inclusion in our forward work programme. These have been taken into account within this report and the underlying evidence base. Explicit responses are included within the Level 2 '*Addressing Regulatory Requirements and Feedback'* report.

We have engaged extensively with the Environment Agency on this topic area as part of the Process by Agreement for the ESC. We received comments on our selection of climate scenarios and shared our Coastal Evolution Projections report [25]. We also adjusted our approach to assessment of impacts during the Period of Authorisation (PoA) to use a higher climate emissions scenario than for other periods following Environment Agency feedback.

2.4 Role in Supporting the 2026 ESC

The projections for site evolution outlined in this report support a range of assessments and arguments presented in the ESC. In addition, the projections have been used to directly inform the development of assessment models that themselves inform the main safety arguments. Thus, the evidence and judgements presented in this report are fundamental to several aspects of importance to the ESC.

The primary underlying driver of site evolution is climate change and associated natural processes. Climate is characterised by many variables and the influence of the climate on the repository system is complex. Influence is enacted by a complex chain of processes; the processes are often non-linear and there are multiple, separate climate-related aspects influencing the system at once.

The key processes by which climate characteristics influence the ESC are summarised in Table 2.1.

Table 2.1: Site evolution processes and their influence on the ESC

Site Evolution Process	Underlying Factors	Effect on ESC	How and Where Addressed
Coastal Erosion	Sea level, storminess and wave characteristics	The timing and nature of coastal erosion of the LLWR influences the calculation of impacts in the coastal erosion pathway.	The assessment of coastal erosion [14] considers the 'low', 'high' and 'reference' emissions scenarios separately, with further 'what-if' cases of extreme sea-level rise.
Coastal Erosion	Sea level, storminess and wave characteristics	The area between the repository and the coast gets progressively smaller, reducing the probability of a well being sunk between the repository and the coast.	Within the assessment of the groundwater pathway [14], the probability of a well being sunk between the repository and the coast is assumed to be proportionate to the area between the repository and the coast, according to the relevant scenarios described within this report.
Coastal Erosion	Sea level, storminess and wave characteristics	Erosion of and dispersal of the contents of the repository acts as an effective ‘end point’ for other pathways.	Groundwater and gas mediated pathways are assumed to end according to the projections of complete facility erosion within this report.

			Human intrusion events relating to scavenging into waste exposed by coastal erosion have regard to the projections within this report but take a more cautious approach by assuming erosion may commence earlier than considered here [14]. This serves to reduce the potential for 'ingrowth' of hazard from long-lived radionuclides.
Infiltration Through the Cap	Hydrologically Effective Rainfall (HER)	Infiltration through the cap is proportional to HER, and a function of the hydraulic conductivity of the cap layers. The uncertainties in the performance of the hydraulic barriers are more significant than uncertainties in HER.	Projections of HER and infiltration are considered within groundwater pathway calculations [14]. In general the influence of changes to and uncertainty in HER is small compared to the uncertainty in cap degradation, and therefore infiltration rates.
Infiltration Through the Cap	General climate	Temperature and humidity could affect the rates of degradation of engineered barriers either directly	Considered as part of the Engineering Performance Assessment (EPA) [12]. Whilst climate change may lead to a

		(through acceleration of chemical processes) or indirectly (if surface vegetation is not maintained and increased cracking/denudation of the cap layers occurs). This in turn would affect infiltration rates.	change in vegetation characteristics, sufficient moisture will always be available in the cap to sustain vegetation and thus resist erosion.
Hydrogeology	HER	HER will affect groundwater flow rates through the geosphere. The hydrogeochemistry may also be affected.	Considered within hydrogeological modelling [7]. In general the influence of changes to and uncertainty in HER is small, because annual HER is not projected to change significantly.
Hydrogeology	Coastal erosion (see earlier table listing)	The receding coast acts as a boundary condition in hydrogeological modelling.	Considered within hydrogeological modelling [7].
Land Use & Human Habits	General climate	A range of potential effects, including: • drinking water and irrigation requirements • changes to agriculture practices e.g. types of	Qualitatively considered within the relevant assessment [14]. In general, habits are set in a cautious manner, so variations due to changes in climate are a minor bias.

		vegetables grown; • lifestyle and habit changes.	
Ecological Characteristics	General climate	Changes to the types of non-human biota present in the vicinity of the site could affect the assessment of impacts to non-human biota.	Qualitatively considered in the '*Assessment of Impacts to Non-human Biota'* report [16]. Not quantitatively considered, and implications are negligible given the standard approach to consider impacts to 'reference' animals and plants.

Given the range of potentially competing effects, it is not feasible, a priori, to identify a single climate case that is cautious or cautiously realistic. For example, more rapid coastal erosion reduces the time for radioactive decay and increases impacts via the coastal erosion pathway but at the same time reduces impacts via the groundwater pathway due to a reduction in the probability of a well between the facility and the coast.

3 Climate Evolution and Sea-level Change

Three emissions scenarios – Reference, Low, and High – are used to capture the range of possible future greenhouse gas pathways. Climate projections at the LLWR site are based on downscaled global models and local meteorological data.

- Reference Emissions Scenario: CO_2 emissions remain at current levels until mid-century before declining.
- Low Emissions Scenario: CO_2 emissions decline rapidly, reaching net zero after 2050, followed by net negative emissions.
- High Emissions Scenario: CO_2 emissions roughly double by 2050, peaking around 2090, with high atmospheric concentrations persisting.

Projected temperature and precipitation changes

Under the Reference Emissions Scenario, mean annual temperature at the LLWR site is projected to peak at +2.4 °C above 1981 to 2010 values around 300 years after present (AP), returning to +0.5 °C by 10,000 years AP. In the Low Emissions Scenario, peak warming is limited to +1 °C at 100 years AP before declining to +0.1 °C by 10,000 years AP. For the High Emissions Scenario, warming is most pronounced, with temperatures reaching a maximum of +7.4 °C at 300 years AP and remaining elevated at +2.6 °C at 10,000 years AP.

The climate maintains a general classification of 'temperate oceanic' under both the Reference and Low Emissions Scenarios, reflecting a biosphere similar to that of the present day. Under the High Emissions Scenario, the climate transitions to a 'humid subtropical' classification for a period, similar to present-day Portugal. Higher emissions scenarios project more intense warming and wetter winters, with drier summers.

Sea-level rise

Relative sea-level rise at the LLWR site is projected to reach 10 m (Reference), 23.3 m (High), or 0.7 m (Low) above present by 10,000 years AP.

These projections are derived from models that integrate both global and local factors influencing sea level. Global eustatic changes, such as thermal expansion of ocean water due to increased temperatures and the melting of polar ice sheets, are combined with local isostatic adjustments. The pattern of rise is not linear, with each scenario characterised by periods of both gradual and more rapid rise.

3.1 Overview

The following subsections describe projections of how the climate may evolve in the future. Particular attention is paid to:

- estimates of future global temperature rise, and associated climatic variations;
- implications for sea-level rise in the vicinity of the LLWR.

These aspects are of specific importance for understanding the LLWR system, as temperature rise provides the driver for global sea-level rise, and the rate and magnitude of rise could both affect the rate of coastal erosion occurring at the adjacent coast and the potential for inundation of the LLWR site. Associated climatic variations are also relevant to considering surface landscape effects, such as the evolution of natural vegetation, land use, crop suitability and surface erosion.

A more detailed overview of the analyses presented in this section can be found in reference [23].

3.2 Drivers for Global Climate Evolution and Sea-level Change

Predictions of the potential future evolution of the climate are complex and subject to a wide range of uncertainties. However, the fundamental factors driving climate evolution arise from:

- variations in the orbital characteristics of the Earth (Milankovitch cycles);
- natural solar variability; and
- changes in the composition of the atmosphere (in terms of changes in carbon dioxide concentrations and sulphate aerosol concentrations).

Whilst Milankovitch cycles are largely predictable, natural solar variability and the evolution of atmospheric composition present greater uncertainties. There is strong scientific consensus that current greenhouse gas concentrations exceed levels observed at any point in the past two million years. The significant increases recorded since the 20th century are conclusively attributed to anthropogenic activities, including energy production, transportation, and agriculture [32]. This is the attributed cause of the observed warming trend in the Earth's climate in the last century: global surface temperature in 2011 to 2020 was 1.1 °C above that in 1850 to 1900 and has increased faster since 1970 than in any other 50-year period in at least the last 2,000 years [32]. While the consequences of this trend on the global climate are broadly understood, predicting the future evolution of greenhouse gas atmospheric concentrations is not straightforward as the contribution of emissions from anthropogenic sources is dependent on political and economic drivers and therefore subject to significant uncertainty.

Additionally, although increases in greenhouse gas concentrations represent a forcing factor for climate change (through radiative forcing, that is trapping of heat within the Earth’s atmosphere), there are important feedbacks that can affect its significance on a local scale. Atmosphere-sea-ice-land feedbacks, atmosphere-ocean feedbacks and changes to ocean circulation patterns act as modifiers to these primary factors.

Climate change will lead to effects such as changes to sea water and land surface temperatures, changes to weather patterns and the nature and frequency of storms. All aspects

will influence factors such as land use (see Section 5). The most important effect from the perspective of the ESC, however, is the rate and extent of sea-level rise that might occur in the vicinity of the LLWR. The likelihood, mode and timing of any disruption of the LLWR site as a result of coastal erosion and/or sea water inundation will depend upon the future evolution of the local sea level.

Sea level is influenced by several processes, including:

- the rate of circulation and thermal expansion of waters within the world's oceans (noting that it can take a long time for expansion due to warming to be fully expressed);
- the rate and extent of glacier and icesheet melting contributions; and
- isostatic uplift or subsidence (for example, in response to tectonics, melting icesheets or the deposition of sediment), which can influence sea level on a local scale.

The following subsections discuss how models have been formulated to support the development of understanding of these aspects and provide projections for climate and sea-level change for the 2026 ESC.

3.3 Present Day Climate Information

To support the 2026 ESC climate projection calculations, we must first define a set of present-day climate characteristics. This is discussed below. More detail can be found in reference [23].

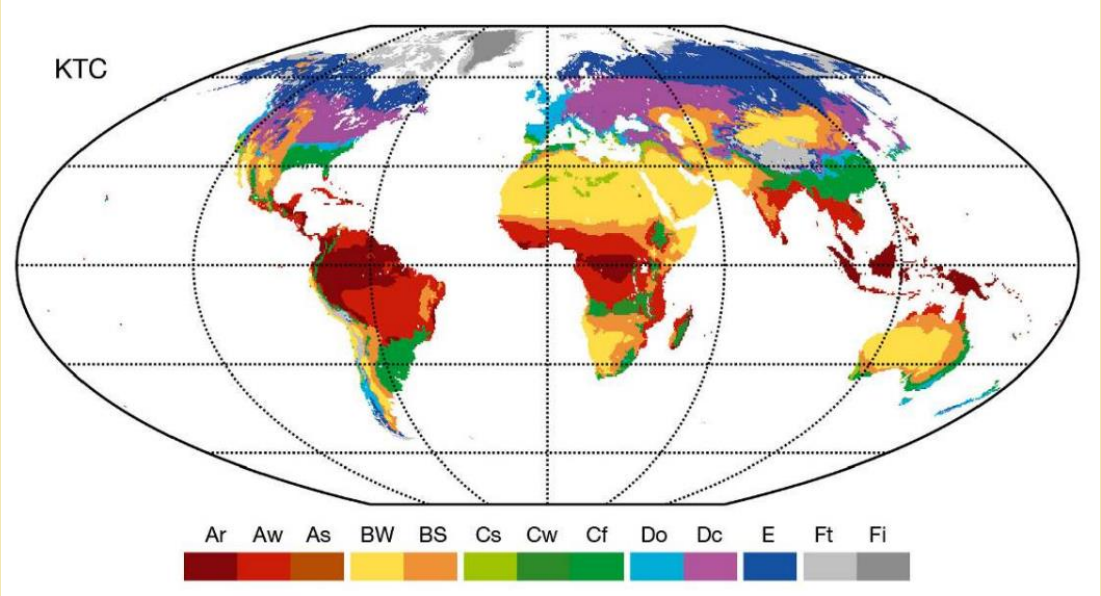
The UK's climate is defined by its cool winters, warm summers and lack of dry season. In the Köppen-Trewartha climate classification (Box 2) it falls within the 'temperate oceanic' (Do) climate category. This classification is characterised by mild temperatures and abundant precipitation (at least four to seven months with a mean temperature of over 10 °C, a coldest month of at least 0 °C and oceanic influences). As its climate classification suggests, the UK's proximity to the Atlantic Ocean exerts a strong climatic influence, leading to a marked east-west variation. Western regions, closest to the sea, are generally more mild, wet and windy with a narrower seasonal temperature variation than in the east. The LLWR site lies on the west coast, so its climate broadly fits this description.

Between 1995 and 2010[5] on the West Cumbrian coast, the mean annual temperature was 9.28 °C and the average total annual precipitation was 1,054 mm y^{-1}. Seasonal variability in temperature and precipitation is observed, albeit with a lack of extremes, with the winter months being typically wetter and cooler than the summer months.

5 This date range was selected to align with the baseline upon which projections into the future are made by the IPCC.

Box 2: The Köppen-Trewartha climate classification scheme

The Köppen-Trewartha climate classification scheme classifies climate according to four components: thermal zone, continentality, humidity, and seasonal distribution of precipitation. Each classification tends to correspond to a dominant vegetation zone, such that the classifications provide a useful tool in the analysis of climate change projections [33].



Climate sub-type	Description
Group A: Tropical humid climates	
Ar	Tropical wet
Aw	Tropical wet-and-dry
Group B: Dry climates	
BW	Arid / Desert
BS	Semi-arid / Steppe
Group C: Subtropical climates	
Cs	Subtropical dry-summer / Mediterranean
Cw	Subtropical humid

Cf	Subtropical dry-winter
Group D: Temperate climates	
Do	Temperate oceanic
Dc	Temperate continental
Group E: Boreal climates	
E	Boreal
Group F: Polar climates	
Ft	Tundra

We have been collecting temperature and precipitation data with a meteorological station on the LLWR site since the early 1990s. Data from the period 1992 to 2010 (for temperature) and 1995 to 2010 (for precipitation) are taken as the baseline climatic conditions for the 2026 ESC climate projections. These dates are slightly different to the baseline of 1981 to 2010 upon which global and national projections have been made. Comparison with observation data at nearby Met Office meteorological stations and Met Office gridded interpolations provide confidence that the climate surrounding the LLWR has been stable over these periods and the site data are appropriate to use as a baseline.

The seasonal fluctuation in temperature at the site is shown in Figure 3.1, illustrating a variation of up to 60% more or less than the annual average temperature in any given month. May to October is warmer than the annual average, and November to April is cooler than the annual average. The seasonal fluctuation in precipitation is shown in Figure 3.2, which shows that February to June are typically drier than October to January.

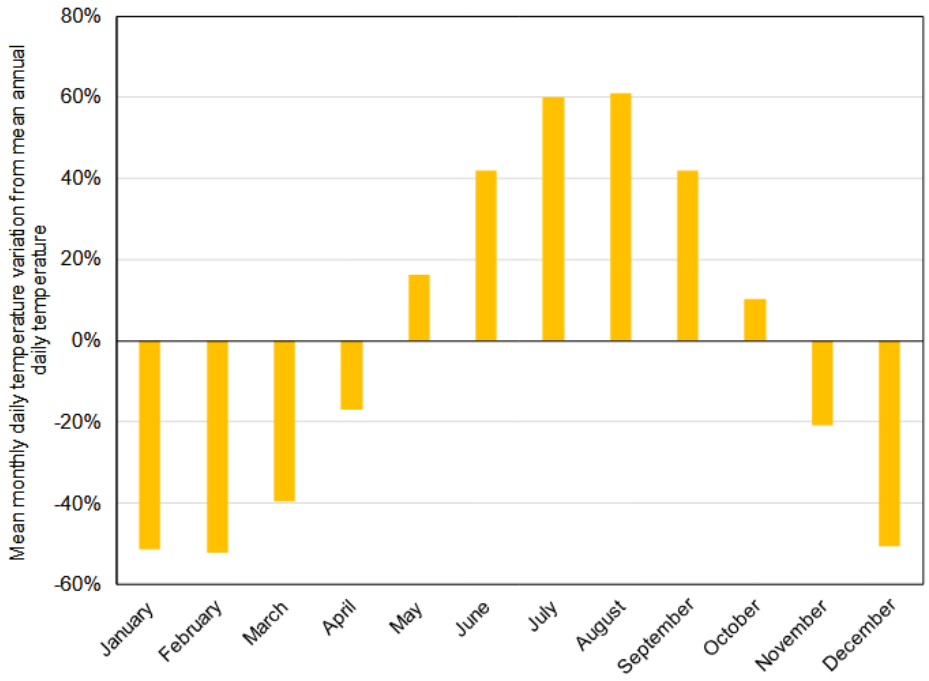


Figure 3.1: Seasonal fluctuation in temperature (%) at the LLWR site

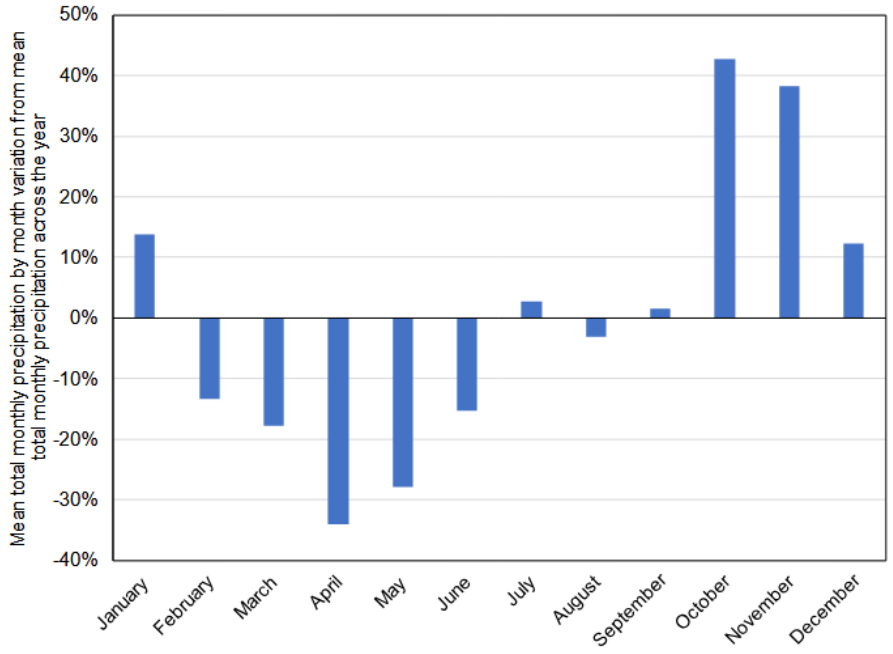


Figure 3.2: Seasonal fluctuation in precipitation (%) at the LLWR site

3.4 Projections for the 2011 ESC

Future projections for climate and sea level used in the 2011 ESC [34] were built upon those informing the 2002 PCSC, which employed the use of the LLN-2D model, an early example of

an Earth Model of Intermediate Complexity (EMIC), which explore, via numerical modelling, the complex inter-relationships between the various factors that contribute to global climate change.

Projections used in the 2011 ESC utilised two EMICs and one simple climate model to study the implications to the year 3000 of six long-term CO_2 emissions scenarios. The EMICs used were:

- GENIE-1 (an established model with a range of past applications, developed as a successor to the LLN-2D); and
- MoBidi (developed in the UK through collaboration between the Natural Environment Research Council (NERC) and the Tyndall Centre).

3.4.1.1 Global Predictions

Results from these projections were interpreted in the context of the worldwide programme of research reviewed by the IPCC. By the end of the 21st century, global temperature was expected to increase by 1.1 to 6.4 °C (relative to the period from 1980 to 1999) and global sea level was expected to rise by between 0.2 to 0.8 m.

In the longer term, best estimates of global sea-level rise over the next 1,000 years, and in a few thousand years when sea-level rise is expected to cease, were 8.5 m and 17.5 m, respectively. These estimates for sea-level rise accounted for contributions from the thermal expansion of ocean water, glacier meltwater, and the melting of ice caps, including the Greenland and West Antarctic Ice Sheets. These projections are illustrated in Figure 3.3.

3.4.1.2 Predictions at the LLWR Site

Up to 100 years from present:

Projections for relative sea-level rise at the LLWR site by the end of the 21st century ranged from 0.14 to 0.74 m, aligning with global estimates of 0.2 to 0.8 m and taking account of isostatic uplift of 0.6 mm y^{-1} at the LLWR site. This level of sea-level rise was not expected to significantly affect the tidal range.

Beyond 100 years from present:

Long-term projections indicated that relative sea level at the LLWR site could rise by 1.1 to 21.1 m over the next 1,000 years, and by 7.3 to 24.6 m over the next 3,000 years.

Beyond 3,000 years from present:

For timescales beyond 3,000 years, sea-level rise was expected to continue, though at a diminishing rate. The projected range was 6.5 to 23.8 m, with a best estimate of 14.9 m.

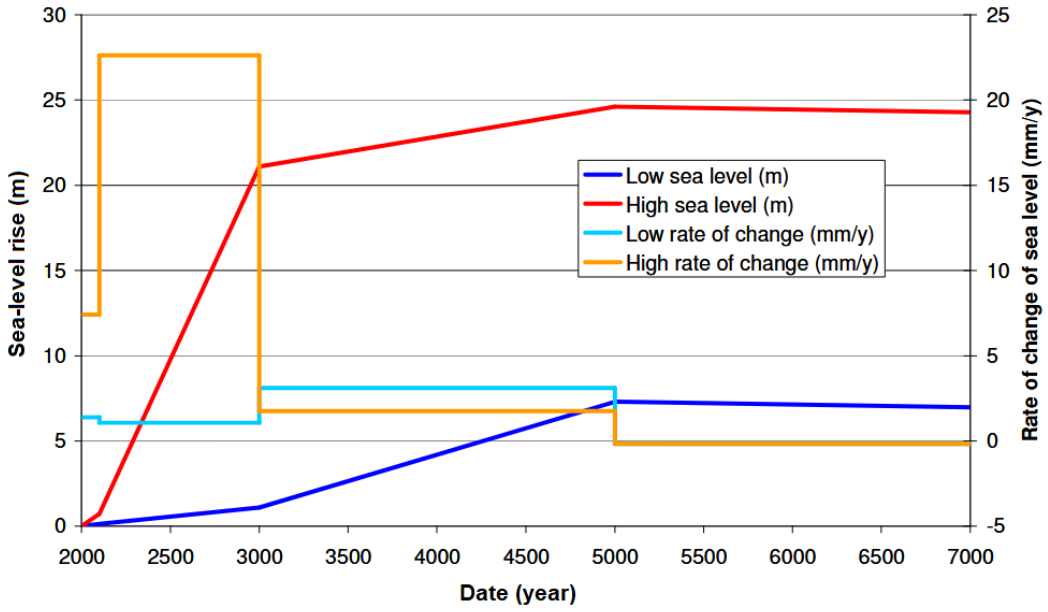


Figure 3.3: Two projected scenarios for sea-level behaviour at the LLWR site used in the 2011 ESC, showing expected sea-level rise and its rate of change

3.5 Climate Projections for the 2026 ESC

3.5.1 Approach

3.5.1.1 Selection of Emissions Scenarios for Use in the 2026 ESC

In making projections of the future climate at the LLWR site, it is necessary first to identify a set of global emissions scenarios to represent the range of potential future climate conditions of interest. This range of climate scenarios is strongly conditioned by assumptions concerning future emissions of greenhouse gases, notably CO_2, and any measures taken to mitigate the effects of such emissions, e.g. through carbon capture and storage.

We have adopted a 'reference' emissions scenario as a basis for all climate projections used in the ESC. This allows all reference case calculations to be made using the same emissions scenario, and is beneficial in that it:

- provides consistent climate projections across the ESC;
- enables a transparent, logical link back to the underlying science;
- has been defined early in the ESC development programme and therefore can be applied consistently throughout the ESC;
- does not skew the scenario towards being cautious or optimistic for any one pathway (see Subsection 2.4).

The Reference Emissions Scenario is based on CO_2 emissions remaining around current levels until the middle of the century before decreasing.

Uncertainty and the implications of alternative emissions pathways are explored via ‘high’ and ‘low’ emissions scenarios. We do not attach a probability to any given scenario, and we will not refer to the reference case as a ‘central’ or ‘most likely’ case. It is notable that, given the range of potentially competing effects, it is not feasible a priori to identify a single climate case that is cautious or cautiously realistic. For example, more rapid coastal erosion reduces the time for radioactive decay and increases impacts via the coastal erosion pathway but at the same time reduces impacts via the groundwater pathway due to a reduction in the probability of a well between the facility and the coast.

We focus on a set of core climate scenarios, and do not explicitly address more extreme or highly improbable climate scenarios in this report. This ensures that the conceptual understanding and projections of site evolution remain grounded in the most scientifically credible and policy-relevant climate trajectories, as defined by current international guidance. However, in the broader ESC assessments, more extreme or “what-if” scenarios are considered where appropriate. These additional cases are used to test the robustness of safety arguments, explore the consequences of highly unlikely but plausible events, and respond to specific regulatory or stakeholder concerns.

Our approach relies to some extent on judgements to select appropriate emissions pathways (although they draw on work conducted by the IPCC [35], discussed shortly). The scenarios selected should be interpreted in the context of providing a reasonable basis upon which to demonstrate and communicate the evolution of the facility and its impacts, with the three scenarios encompassing a suitable range. The exception is for the PoA, for which we adopt the High Emissions Scenario as a central case in our assessments, reflecting regulatory advice.

Both the selection of scenarios and evaluation of their climatic implications rely mainly upon recent work of the IPCC [35]. The IPCC’s recent projections for future climate change are based on Shared Socio-economic Pathway (SSP) scenarios, in contrast to its previous approach utilising Representative Concentration Pathway (RCP) scenarios. RCP scenarios formed the basis for the UK-specific projections given by the UKCP18 project which inform the 2026 ESC.

3.5.1.2 Climate Projections to 2100

Climate change projections up to 2100 are based on the global climate models defined by the IPCC [35]. Typically, these climate projections are made using models with a grid scale of 100 km or more. This scale is too coarse to be appropriate for making predictions at the LLWR site, whose coastal location and proximity to mountains makes its climate more localised. Such spatial variability is not adequately captured by a 100 km grid scale so downscaling of results is required.

The UKCP18 model provides UK-specific probabilistic projections of climate-related variables (relative to mean climatic conditions over the period 1981 to 2010) on a 25 km grid scale through the downscaling of IPCC models. This is achieved through 'dynamical downscaling', where the higher resolution, smaller (25 km grid) model takes information from the larger

domain model as a starting point for its simulation. Probabilistic projections are then produced using a statistical downscaling approach. Finer UKCP18 projections to a 5 km grid were used to support the adoption of baseline climate parameters at the LLWR site.

3.5.1.3 Climate Projections Beyond 2100

Most climate projections, such as those provided by the IPCC and UKCP18, only extend for a few hundred years into the future, and the IPCC's SSP and RCP emissions scenarios are only defined to 2100. This is insufficient to support the ESC, which assess impacts many thousands of years into the future, so it is necessary to extrapolate results to longer timescales. This can be achieved by first considering that the IPCC [35] affirms with high confidence that there is a near-linear relationship between cumulative anthropogenic CO_2 emissions and the global temperature they cause. A scaling factor describing this linear relationship can be obtained from the mean global temperature projections published by the IPCC [35] and applied to emissions scenarios to extrapolate mean global temperature beyond 2100. This scaling factor is obtained by considering that each 1,000 Pg of cumulative CO_2 emissions (corresponding to 270 Pg C) is assessed to likely cause a 0.27 to 0.63 °C increase in global surface temperature with a best estimate of 0.45 °C to be used in the scaling factor.

Extended versions of the RCP emissions scenarios projecting changes in atmospheric CO_2 concentrations from 2,000 to 2,500 are defined by reference [36]. These can be used to make climate projections up to one million years after present, utilising a carbon cycle impulse model to calculate the response of atmospheric CO_2 concentrations to emissions and a statistical emulator to project the future evolution of climatic parameters in response [23]. The extended emissions scenarios selected for consideration in the 2026 ESC are shown in Table 3.1.

Given the simplicity of these extended emissions scenarios and the linear relationship between emissions and global temperature, they can be extended beyond 2500 AD for use in longer-term projections, as demonstrated in reference [37] in making projections of global sea-level change for the next 10,000 years, and by the IAEA [38] in developing an understanding of the implications for geological disposal of long-term changes in the biosphere.

Table 3.1: Summary of emissions scenarios, including their mapping to SSP and RCP scenarios featured in reference [35] and [39], respectively. SSP and RCP scenarios are only defined to 2100, so the emissions scenarios beyond this time are based on the extended emissions scenarios presented in reference [36]

Emissions Scenario	Description	Equivalent IPCC/UKCP scenario
Reference	CO_2 emissions remain around current levels until the middle of the century before decreasing. Total net emissions by 2500 of 1,000 Pg of carbon.	SSP2-4.5 / RCP4.5
Low emissions	CO_2 emissions decline to net zero after 2050, followed by net negative CO_2 emissions. Total net emissions by 2500 of 70 Pg of carbon.	SSP1-2.6 / RCP2.6
High emissions	CO_2 emissions roughly double from current levels by 2050, peaking around 2090. Peak atmospheric CO_2 concentrations occur around 2240. Total net emissions by 2500 of 5,000 Pg of carbon.	SSP5-8.5 / RCP8.5

3.5.2 Temperature Projections

We obtained temperature projections by scaling global temperature projections to account for regional variations. Global temperature projections to 100 years after present (AP) were taken from reference [35] using SSP emissions scenarios; projections to 300 years AP used extended SSP emissions from the same source; and projections beyond 300 years AP were derived using a carbon cycle impulse model developed in reference [40] predicting the response of atmospheric CO_2 concentrations to the extended SSP emissions scenarios [23]

Global temperature projections were aligned with UKCP18 climate scenarios, and a linear scaling approach was applied to translate these global trends into regional temperature projections specific to the LLWR site. The mean annual temperature projections resulting from this process are shown in Table 3.2 and Figure 3.4, which show annual average temperature peaking at 300 years AP for all emissions scenarios before declining to 10,000 years AP. The

climate projections for the 2026 ESC are valid through 10,000 y AP. No account has been taken for the potential for glaciation, as there is scientific consensus that the next glaciation period would not occur for at least 50,000 years [41].

The difference between mean monthly temperatures and the annual average for each emissions scenario indicates that, as emissions increase, the seasonal cycle becomes less pronounced in terms of percentage variation throughout the year (see Figure 3.5). This indicates that a greater degree of global warming would result in a lesser seasonal temperature variation i.e. the relative difference between summer and winter temperature reduces with increased overall temperature. The absolute values of monthly temperature are given in Section A.5 of Appendix A in reference [23].

Table 3.2: Changes in average temperature (°C) at the LLWR site relative to 1981 to 2010 at various times AP for the three scenarios of relevance to the 2026 ESC

2026 ESC Emissions Scenario	Increase in mean temperature (°C)				
	100 y AP	300 y AP	1,000 y AP	3,000 y AP	10,000 y AP
Reference	1.88	2.39	1.88	1.45	0.51
Low	1.01	0.78	0.70	0.47	0.08
High	3.16	7.37	6.81	5.51	2.59

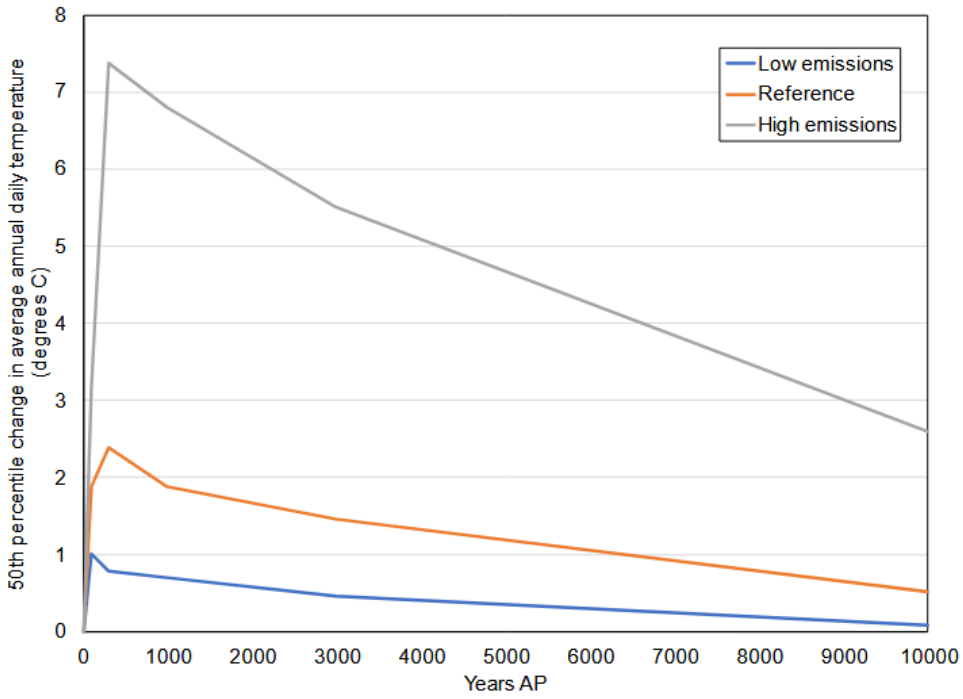


Figure 3.4: Changes in average temperature (°C) at the LLWR site relative to 1981 to 2010 at various times AP for the three scenarios of relevance to the 2026 ESC

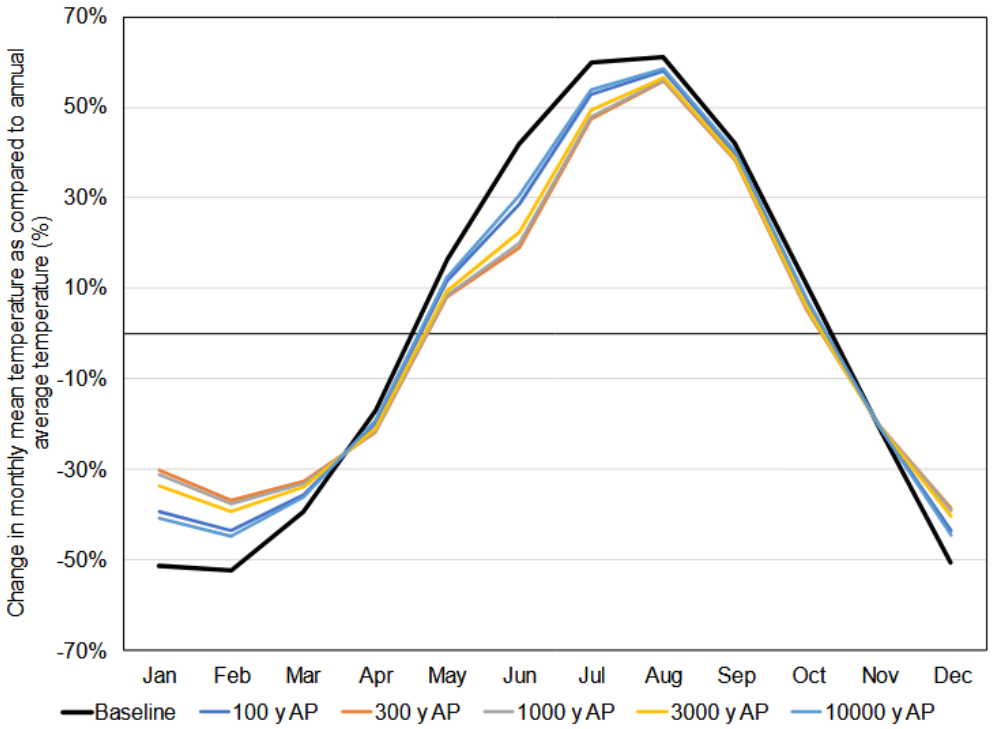


Figure 3.5: Percentage change in mean monthly temperature (compared with annual average) for the High Emissions Scenario

3.5.3 Precipitation Projections

The approach to making projections of precipitation follows the same methodology as that for temperature projections; these projections are shown in Table 3.3 and Figure 3.6. The trend exhibited is similar to that seen for the temperature projections, whereby precipitation peaks at 300 years AP before decreasing to 10,000 years AP.

The variation in monthly mean precipitation (compared with the annual average) for each of the emissions scenarios shows that the seasonal cycle strengthens, in terms of percentage variation over a year, with increased carbon emissions (Figure 3.7). This shows that increased warming would lead to increasingly drier summers and wetter winters. Absolute values of monthly precipitation are given in Section A.5 of Appendix A of reference [23].

Table 3.3: Changes in annual average precipitation (%) at the LLWR site relative to 1981 to 2010 at various times AP for the three scenarios of relevance to the 2026 ESC

2026 ESC Emissions Scenario	Mean annual precipitation change (%)				
	100 y AP	300 y AP	1000 y AP	3000 y AP	10,000 y AP
Reference	4.3	5.4	4.3	3.3	1.2
Low	2.2	1.7	1.5	1	0.2
High	6.9	16.1	14.9	12	5.7

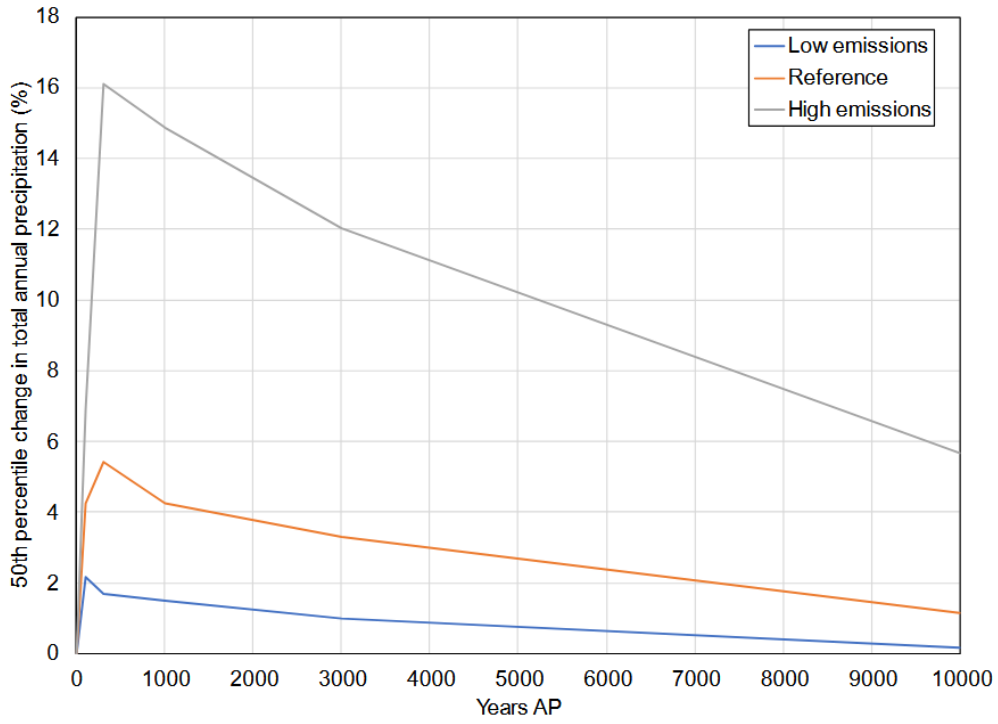


Figure 3.6: Changes in annual average precipitation (%) at the LLWR site relative to 1981 to 2010 at various times AP for the three scenarios of relevance to the 2026 ESC

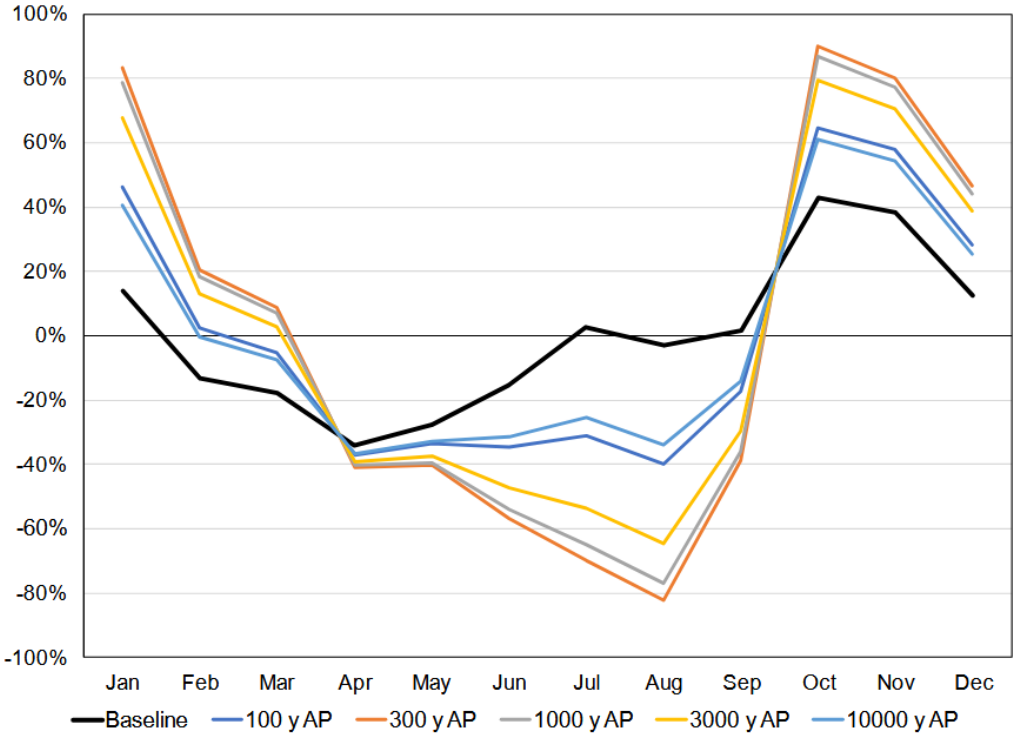


Figure 3.7: Percentage change in mean monthly precipitation (compared with the annual average) for the High Emissions Scenario

3.5.4 Potential Evapotranspiration

Potential evapotranspiration (PE) is the loss of water from the Earth's surface through evaporation and transpiration, assuming an unlimited water supply and taking into account atmospheric conditions such as temperature, humidity, sunlight and wind. Having calculated changes in temperature and precipitation for all three of the scenarios of interest at various times AP, it is possible to use those data to estimate changes in PE with changing temperature.

PE projections were thus calculated in reference [23] based on the approach defined in reference [42] (see Box 3), which yielded results that were consistent with other comparable studies. The change in annual PE (%) is summarised in Table 3.4 for each of the climate scenarios of interest to the 2026 ESC, given against a baseline period of 1992 to 2010.

Being influenced by atmospheric conditions, PE projections exhibit variation in line with seasonality, typically being highest in summer and lower in the winter. PE projections on a seasonal basis may therefore be more useful than an annual figure.

Box 3: Method for calculating PE.

Method for calculating Potential Evapotranspiration (PE) changes (developed by Oudin et al. [42])

PE is the loss of water from the Earth's surface through evaporation and transpiration, assuming an unlimited water supply and accounting for atmospheric conditions such as temperature, humidity, sunlight and wind. PE can be calculated using the approach developed by Oudin et al. [42]:

$$PE = \frac{\left(\frac{R_e}{\gamma \rho}\right)(T_a + 5)}{100} \qquad T_a + 5 > 0$$

$$PE = 0 \qquad T_a + 5 \leq 0$$

where *PE* is the rate of potential evapotranspiration (mm d^{-1})

R_e is extra-terrestrial radiation (MJ m^{-2} d^{-1})

λ is the latent heat flux in (MJ kg^{-1})

ρ is the density of water (kg m^{-3})

T_a is mean air temperature (°C), derived as a long-term average

The change in PE with a change in temperature is of most significance in the context of assessing the effects of climatic change at the LLWR site. In the above equation, R_e can be treated as constant because it depends on geographical location and Julian day rather than temperature, and varies slowly in the long term as a consequence of quasi-periodic variation in the orbit of the Earth. At the LLWR site, $T_a + 5$ is always non-negative. Therefore, changes in PE can be calculated according to:

$$PE_{new} = PE_{old} \frac{(T_{a,new} + 5)}{(T_{a,old} + 5)}$$

where mean monthly values are used for T_a and the subscripts 'old' and 'new' indicate the original and modified values of T_a and PE.

Table 3.4: Changes in total annual PE (%) at the LLWR site relative to 1992 to 2010 at various times AP for the three scenarios of relevance to the 2026 ESC

2026 ESC Emissions Scenario	Total annual PE (%) change				
	100 y AP	300 y AP	1,000 y AP	3,000 y AP	10,000 y AP
Reference	13	17	13	10	4
Low	7	5	5	3	1
High	22	52	48	39	18

3.5.5 Qualitative Projections of Factors Influenced by Climate Change

Changes in climate and sea level may impact processes of significance to the ESC such as those affecting erosion of the coastline and the evolution of the inland landscape. These are discussed below.

3.5.5.1 Controls on Coastal Erosion

Consideration of coastal erosion is crucial to understanding the evolution of the LLWR site. Over long timescales it is a function of sea-level rise and sediment budget, but the mechanisms driving erosion are primarily related to wave power and extreme water levels (further discussed in Section 4). These are influenced by phenomena that may be affected by climate change, such as the severity and frequency of storms and storm surges.

Ocean waves are primarily driven by wind. When this occurs at great distances offshore the waves are felt as swell, which have longer wavelengths than waves generated near the shore. Thus, an increase in storm intensity can result in increased wave-power available to drive coastal erosion. Likewise, increased storm frequency plays an important role in driving coastal erosion. Storm clustering, where the shoreline is persistently exposed to increased wave heights, causes more extreme coastal erosion than a single storm with wave power equivalent to the cumulative wave power of the storm cluster. This is because the first storm strips the beach leaving cliffs exposed to erosion during subsequent storms.

Upper-ocean warming, a consequence of global warming, has been identified as a factor that is increasing wave power globally [43]. However, while there has been an observed increase in storm frequency and peak wave heights over the last 40 years in the UK [25], the high variability and limited understanding of the driving mechanisms mean that these trends cannot be directly attributed to climate change [44]. Therefore, in the ESC, the magnitude and frequency of storms are considered to remain at present levels.

Extreme water levels along the LLWR coastline may also be influenced by storms. Storm surges are characterised by a short-lived increase in water level above the expected astronomical tide. These arise when large swells caused by the high winds and low pressure associated with storms at sea combine with the effect of astronomical tides. The impact of climate change on storm surges is difficult to quantify and there is no conclusive evidence that they will increase over next hundred years. The impacts over longer timescales are even more uncertain. No evidence for significant changes in magnitude or frequency of storm surges has been found in UKCP18 projections [23]. Furthermore, the relatively high speed that storms pass through West Cumbria coupled with the high tidal range results in a relatively low probability of a storm surge occurring during high tide [25]. Therefore, for the purposes of the ESC the magnitude and frequency of storm surges are assumed to remain at present levels.

3.5.5.2 Controls on Inland Landscape Evolution

A range of processes are likely to influence the evolution of the inland landscape in the vicinity of the LLWR. The nature and extent of a number of these processes will depend upon the evolution of the climate. Such processes include:

- temperature and precipitation, including their seasonal variation, which affect groundwater recharge and infiltration (e.g. into engineered domains);
- erosion processes, which lead to topographic changes;
- changes in land usage arising from altered surface landscape and vegetation characteristics;
- the nature (meander patterns, water heights, flow rates, etc.) of water features such as the Drigg Stream and the Irt and Ehen rivers;
- degradation of land quality on the seaward side of the site in response to coastal erosion and subsequent movement of the saline/freshwater interface.

These processes are of relevance to assessment models (for example, altered vegetation characteristics affect the definitions of human and non-human biota) and other aspects of the safety case, so it is important to consider the evolution of the inland landscape. One way to achieve this is to consider the climate classifications associated with each of the projected emissions scenarios. Climate classification schemes such as the Köppen-Trewartha scheme use temperature and precipitation characteristics to describe the qualitative nature of a climate and its vegetation characteristics.

Reference and Low emissions scenarios

In both the Reference and Low emissions scenarios, the climate classification according to the Köppen-Trewartha scheme throughout the projections remains ‘temperate oceanic’ (Do). Precipitation would not increase significantly from that observed at the present day, so it is reasonable to expect little change in vegetation characteristics and farming practices. However, soils will be increasingly drier throughout the summer months in both scenarios compared with

the baseline conditions, so will be less able to cope with more extreme rainfall and the higher winter rain. This could influence rainfall infiltration, groundwater recharge and erosion rates, although they are not expected to alter drastically.

High Emissions Scenario

In the High Emissions Scenario, a ‘temperate oceanic’ (Do) classification is expected before 300 and beyond 3,000 years AP. The period between 300 and 3,000 years AP has a warmer climate classification, ‘humid subtropical’ (Cf) in the Köppen-Trewartha climate classification, with mean monthly temperatures of >10 °C persisting for most or all the year. With these warmer, wet conditions throughout the year, present-day coastal Portugal (as a coastal area with a Cf classification) would provide a useful analogue for potential vegetation and agricultural regimes. Natural vegetation profiles and crop types are likely to change in response, although vegetation cover is expected to remain significant. This would help maintain low rates of soil erosion, although increased rainfall and storms could cause this to increase.

3.5.5.3 Controls on Evolution of the Engineered Barriers

The engineered barriers of the LLWR perform functions to isolate and contain the waste. Understanding how they evolve and perform over time is thus an important input to the wider ESC. The influence of climate on the evolution of the engineered barriers of the LLWR is discussed in the *'Engineering Performance Assessment'* report [12] and summarised here.

In principle, desertification could lead to enhanced erosion of the cap. However, this is not anticipated. The climate projections provide confidence that, while drier summers may become the norm as climate change progresses, precipitation will remain significantly in excess of evapotranspiration, not least due to wetter winters. That is, there is confidence that sufficient moisture will always be available in the cap to sustain vegetation and thus resist erosion. With somewhat warmer and drier summers, the balance of vegetation types may shift towards flora more similar to those associated with the wetter of the present-day Mediterranean climates. There may be an increase in storminess and thus, in principle, an increase in erosive potential, in particular for climate scenarios considered involving higher levels of change, but there is confidence that a vegetated cap will remain resilient to such processes. The bio-intrusion layer ensure that a change in vegetation to deeper-rooting plants would not damage the functional cap layers.

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may be an increase in storminess and thus, in principle, an increase in erosive potential, in particular for climate scenarios considered involving higher levels of change, but there is confidence that a vegetated cap will remain resilient to such processes.

Another consequence of enhanced storminess and associated extreme events could be temporarily enhanced run-off and overwhelming of the perimeter drains. However, these would be transitory processes, and the overall performance of the cap would not be affected while the performance of one or both elements of the composite geomembrane and BES barrier remains - long term evolution is dominated by temperature and chemistry.

3.6 Sea-level Change Projections for the 2026 ESC

Sea-level change at the LLWR site is a function of eustatic and isostatic sea-level changes:

- Eustatic changes relate to the volume of water in the ocean. They are mainly influenced by changes in the mass of continental ice sheets and ice caps and thermal expansion of ocean water. This is explored in Subsection 3.6.1.
- Isostatic changes are local and are caused by subsidence or uplift in response to tectonics, ice sheet loading or unloading or sediment compaction. At the LLWR site, isostatic uplift is occurring due to continuing recovery from the loading imposed at the time of the Last Glacial Maximum. This is explored in Subsection 3.6.2.

Projections for sea-level change take both these aspects into account to quantify the projected evolution of sea level and coastal recession.

3.6.1 Global (Eustatic) Sea-level Change

The IPCC [35] has commented that it is virtually certain that global mean sea level will continue to rise over the 21st century. Global eustatic sea-level projections are based on arguments and data presented in reference [23]. The relationship between global temperature and sea-level change is complex, arising from several processes that do not follow a simple or consistent relationship. We have applied a bespoke approach, investigating the effect of global temperature over the timescales of interest on each of the processes that contribute to sea-level rise. The contribution of these processes to sea-level rise has been calculated to develop projections of global eustatic sea-level rise at various times in the future (100, 300, 1,000 y AP) for each of the three emissions scenarios (Table 3.5). The factors considered were:

- Thermal expansion of seawater as the oceans warm. Heat transferred to the oceans as the atmosphere warms initially at the surface, extending to full ocean depths on the order of thousands of years. This means that a time lag between atmospheric temperature increase and associated sea-level rise is to be expected. Based on the coefficient of expansion of water and the depth of ocean basins, a rise in atmospheric temperature of 1 °C would increase sea level by approximately 0.76 m. Thus, global

temperature rises of a few degrees would be expected to increase global sea level by a few metres via this process.

The introduction of additional water into the oceans due to melting and loss of mechanical stability of a) ice caps and valley glaciers, b) the Greenland Ice Sheet and c) the Antarctic Ice Sheets (further divided into the West Antarctic Ice Sheet and the East Antarctic Ice Sheet).

Table 3.5: Total global mean sea-level rise at various years in the future for the three scenarios of relevance to the 2026 ESC, relative to the period 1995 to 2014

2026 ESC Emissions Scenario	Global mean sea-level rise (m) relative to 1995 to 2014			
	100 y AP	**300 y AP**	**1,000 y AP**	**(Far future) equilibrium**
Reference	1.00	3.09	5.16	11.30
Low	0.41	1.10	1.57	1.84
High	1.50	4.20	14.42	24.50

The contribution of thermal expansion to sea-level rise is a gradual process that will occur over very long timescales. Indeed, the IPCC [35] has high confidence that sea-level rise due to ocean thermal expansion would not reverse for several centuries to millennia even if CO_2 emissions become net negative. In contrast, contributions from the loss of polar ice are expected to be expressed over shorter and intermittent episodes relating to thresholds at which Antarctic and Greenland Ice Sheets lose stability. The uncertainties associated with these processes are significant, and they have the potential to affect sea-level rise by 10 m or more per degree of warming.

The contributions of the different processes affecting eustatic sea-level change therefore dominate at different times. This is illustrated for the Reference Emissions Scenario in Figure 3.8. For the first 1,000 years AP, thermal expansion of seawater and mass loss from the Greenland ice sheet are projected to contribute most to sea-level rise. Mass loss from the Antarctic ice sheets then contributes most to the longer-term equilibrium sea level.

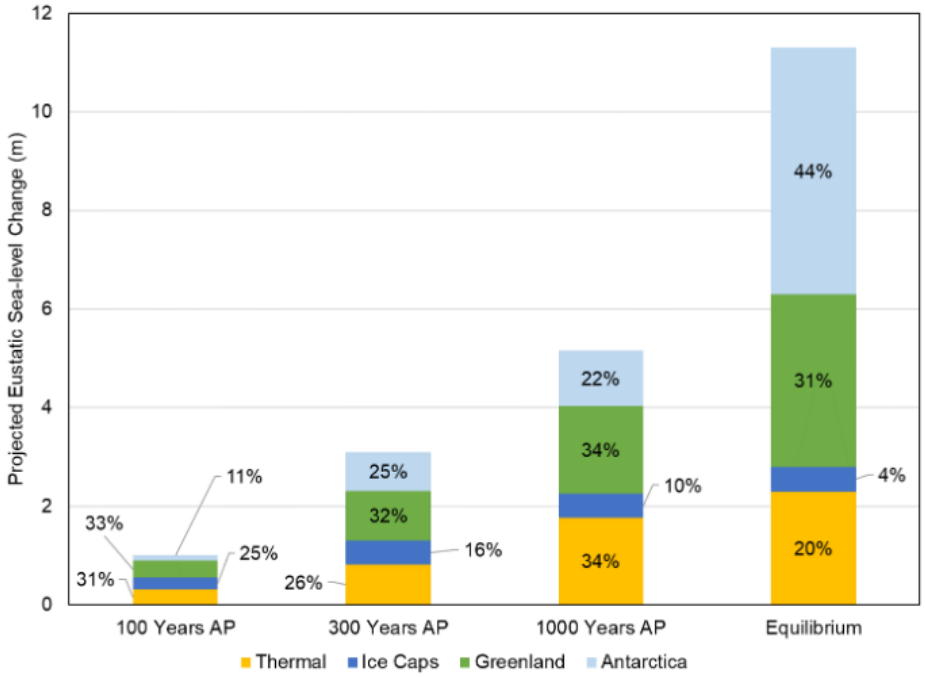

Figure 3.8: Contributions to global eustatic sea-level change for the Reference Emissions Scenario (percentages are rounded to the nearest integer, so may not sum to 100%) [23]

3.6.2 Projected Relative Sea-level Change in the Vicinity of the LLWR

To make projections for relative sea-level change in the vicinity of the LLWR, a correction for local isostatic uplift or subsidence must be applied to the global eustatic projections. To derive an estimate for this isostatic adjustment, we consider empirical data and modelled predictions of past sea level relative to the present day at four locations in the proximity of the LLWR site [45].

Empirical models show no clear correlation between time and relative sea level (their scatter over the last 5,000 years corresponds to uncertainty in uplift rate of 0.2 mm y^{-1}), so predictions from three glacial isostatic adjustment (GIA) models, which estimate isostatic rebound around the British Isles, are used to provide an estimate for isostatic adjustment. An isostatic adjustment of 0.3 mm y^{-1} (with an upper and lower bound of 0.6 mm y^{-1} and 0.01 mm y^{-1}, respectively) accounts for the present-day rate of isostatic uplift, with the rate of rebound assumed to decay with a half-life of 3,000 years.

To apply this isostatic adjustment to the global eustatic sea-level predictions, predictions for global eustatic sea-level change given in Table 3.5 have been described by a series of analytical functions (linear to 300 years AP; exponential beyond 300 years AP), from which the correction for isostatic uplift can be subtracted. The resulting projections for the change in relative sea level at the LLWR site for the three emissions scenarios of interest to the 2026 ESC are shown in Table 3.6 and Figure 3.9.

Table 3.6: Net sea-level rise (m OD) in the vicinity of the LLWR site to 10,000 years AP, accounting for both eustatic and isostatic effects

2026 ESC Emissions Scenario	Relative sea-level at LLWR site (m OD) at various years AP				
	100	300	1,000	3,000	10,000
Reference	0.97	3.00	4.74	7.76	10.10
Low emissions	0.38	1.01	1.30	1.18	0.67
High emissions	1.47	4.11	14.15	22.49	23.33

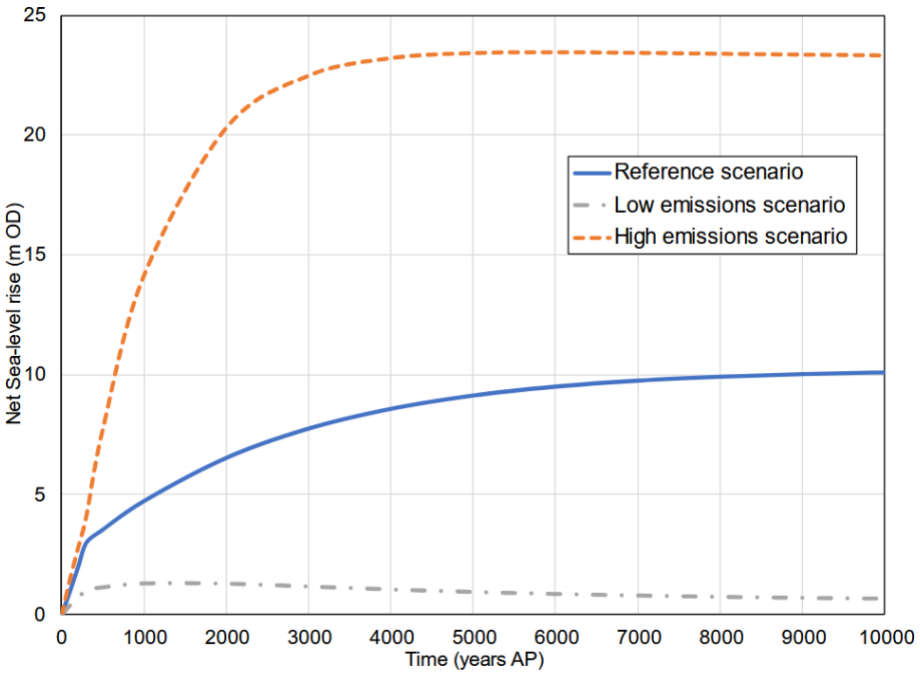

Figure 3.9: Sea-level projections (m OD) in the vicinity of the LLWR site to 10,000 years AP, accounting for both eustatic and isostatic effects

Sea-level projections for the 2026 ESC are higher than projections published by the IPCC [35] and UKCP18 for the earlier periods for which the comparison is available. This is in part because the 2026 ESC estimates make use of local data when considering the potential effects of isostatic adjustment, but also reflects differences in the timing, rather than magnitude, of some contributions to sea-level rise. However, compared with the 2011 ESC, 2026 ESC projections for the High Emissions Scenario are slightly lower, while the 2026 ESC Reference Emissions Scenario projection is similar to the low projection used in the 2011 ESC. This reflects improved modelling techniques and increased confidence in the respective scenarios and models.

3.7 Summary of Progress Since the 2011 ESC

Methodological improvements

The most significant methodological improvement to making climate and sea-level projections for this ESC compared with the 2011 ESC is the adoption of three emissions scenarios on which all projections are based. This allows for better comparison of different climate variables and sea-level projections, both within this ESC and with wider literature, since the emissions scenarios adopted are consistent with those defined by the IPCC [35]. Predicting greenhouse gas emissions is subject to significant uncertainty owing to its dependence on political and economic drivers. The use of three scenarios covering a range of possible emissions profiles explores the uncertainty inherent in making projections of climate and sea-level rise based on such emissions scenarios, as well as accounting for the uncertainty in modelling complex climate processes for which there is little in the way of analogues or validation.

Climate models underpinning predictions in this ESC have also improved since the 2011 ESC. Physical processes, such as ice-sheet dynamics, ocean currents, and ocean-atmosphere interactions are better understood and represented, and a higher spatial resolution output allows for more detailed regional projections. Compared with the 2011 ESC, additional or more detailed projections of climate-related factors such as temperature, precipitation and PE have been presented, for example, emphasising their seasonal variability.

Climate projections in this ESC benefit from enhanced methods for extrapolating beyond the timescales featured in reports by the IPCC, which only extend to 2100, allowing for projections to be made to 10,000 years AP rather than 3,000 y AP as presented in the 2011 ESC.

Differences in the projections

The 2011 ESC projected that sea level would continue to rise beyond timescales of 3,000 years, though at a diminishing rate. The projected range was 6.5 to 23.8 m, with a best estimate of 14.9 m. This is comparable to the projected sea-level rise for the Reference Emissions Scenario in the 2026 ESC (projected to reach 10 m at 10,000 years AP). However, projections for the Low and High Emissions Scenarios in this ESC are lower than (at 0.7 m) and similar to (at 23.3 m), respectively, the 2011 estimate.

4 Coastal Landscape Evolution

Site disruption and erosion

Currently, the closest point of the LLWR vaults lies approximately 350 m inland from the present-day coastline, which is gradually eroding. With sea levels due 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 our understanding of the coastal system and quantitative modelling studies, we have concluded that the disposal vaults will begin to be eroded on a timescale of several hundred to a few thousand years.

Several complementary modelling approaches have been deployed to forecast the rates and mechanisms of coastal erosion and to estimate the timing of repository site disruption at the LLWR facility. These approaches include the use of both empirical and process-based tools such as the bespoke Coastal Recession Model (CRM) and the Soft Cliff and Platform Erosion (SCAPE) model, which are further supported by analyses of historical shoreline movement and the application of straightforward geometric projections.

The principal processes leading to repository disruption are anticipated to include progressive undercutting of coastal cliffs, direct wave attack on exposed engineered structures, and, particularly under the High Emissions Scenario, episodic or sustained inundation due to rising sea levels. These mechanisms, acting in combination with ongoing coastal retreat, will ultimately result in the gradual exposure, fragmentation, and dispersal of repository materials into the adjacent coastal environment.

Waste and engineered material behaviour

Analyses of analogous sites and coastal monitoring have improved understanding of the fragmentation and dispersal of engineered and waste materials in coastal environments.

At the time of initial disruption, waste containers and engineered barriers within the repository will have already experienced varying degrees of physical and chemical degradation. This degradation could diminish their structural integrity, influencing both their ability to resist further coastal erosion and the likelihood of waste material release and dispersal.

As the coastline recedes and erosion reaches the vaults, waste and engineered materials will fall onto the adjacent beach. The beach will consist of a mixed assemblage of natural, engineered and waste materials, including sand, gravel, eroded concrete fragments from the repository structures, and possibly residual waste items that prove more resistant to weathering and transport. These materials will interact with tidal and storm-driven processes, affecting their distribution along the coastal zone and potentially further afield. They will ultimately break up to fine-grained materials and be transported offshore.

4.1 Overview

This section presents projections of future coastal landscape change in the vicinity of the LLWR and summarises the underpinning rationale and evidence. It describes the coastal processes that currently operate (Subsection 4.2) and projections of the likely future evolution of the coast in the vicinity of the LLWR (Subsection 4.3).

4.2 Coastal Evolution Conceptual Model

This section presents a conceptual model of the coastal environment within the vicinity of the LLWR site. Processes, such as erosion and sediment movement, influencing the formation and evolution of coastal geomorphology are discussed. This provides a framework that can be used to assess how these features might evolve in response to a changing climate.

4.2.1 Factors Controlling Coastal Evolution

The mechanisms by which coastal evolution could disrupt the LLWR principally relate to the rate of erosion of beaches and recession of associated cliffs, followed by the transfer of sediment from the beaches and cliffs and into the marine system. Local sediment transport is influenced by several factors, which include:

- the sea level and its rate of change (discussed in Section 3);
- regional sediment transport processes;
- the geology and morphology of the coastline;
- the influence of tides and the local wave regime;
- the characteristics of sediments and materials that might be eroded to form sediments, including the waste and engineered barriers;
- other factors such as the influence of estuaries.

Projections of coastal evolution therefore require these factors to be adequately characterised. In doing so, it is important to understand whether the local sediment system is essentially self-contained or whether sediment material might be continually transported into or out of the local coastal system. This is strongly dependent on the predominant direction of sediment movement along the coastline. The physical characteristics of the sediment (especially size) are a further important factor as they influence how readily it is transported.

On this basis, a sediment budget can then be developed from factors such as the coastal geomorphology and the influence of tides and the local wave regime, to establish whether the coast is presently accreting (a positive budget), eroding (negative budget) or stable (balanced budget). This understanding can then be further developed to provide a conceptual model of the processes governing the likely future evolution of the system.

4.2.2 Historical Coastal Evolution

Historical coastal change over the last approximately 160 years has been assessed in order to understand the importance of relevant controls on coastal development in the vicinity of the LLWR. Coastal change has been assessed using historical Ordnance Survey (OS) maps and aerial photographs alongside more recent aerial photography to calculate annual rates and patterns of shoreline change over the following timeframes:

- Long term (1863 to 2002): Historical OS maps compared with 2002 OS MasterMap;
- Medium term (1941 to 2002): Ortho-rectified historical aerial photos compared to the 2002 baseline survey;
- Short term (2002 to 2009): Comparison of the 2002 baseline survey with the 2009 repeat baseline survey.

Overall, shoreline changes shown by these data sources indicate low rates (typically within ±0.2 m y^{-1}) of both erosion and accretion, with no consistent pattern of advance or retreat over the whole frontage.

Since 2009, regular LiDAR surveys have been flown to support the EA's regional coastal monitoring programme. As such, in addition to maps and aerial photographs noted above, LiDAR surveys undertaken between 2002 and 2022 are used to estimate the rate of erosion in the last 20 years. They indicate that the average rate of erosion at Barn Scar between 2013 and 2020 was 0.7 m y^{-1}, which contrasts to a rate of 0.05 m y^{-1} for the period 2002 to 2009. This increase may be attributed to the 2013/14 winter storm surges or a sustained period of localised beach lowering associated with a net directionality of sediment transport. It is also worth noting that the LiDAR data have a pixel resolution of 1 m (compared with 12.5 cm or less for recent aerial imagery) meaning the assessment of change is suitable for consideration only of longer-term coastal evolution.

4.2.3 Coastal System Geomorphology

Present-day coastal features

The coast in the vicinity of LLWR consists of a series of subtle headlands and bays punctuated by rivers and estuaries (Figure 4.1). Features that are prominent from a geomorphological perspective, some of which form barriers to sediment transport along the coastline, are:

- the headlands at Barn Scar, Whitriggs Scar, Nethertown and St Bees Head; and
- the fan deltas and channels of the rivers Pow Beck, Ehen and Calder and the Ravenglass Estuary.

Features closest to the LLWR site include the Carl Crag embayment, Barn Scar and the Drigg Dunes promontory. Each of these elements represents a variation on the general coastal type: Carl Crag is an example of episodically eroding cliff and dune frontage; the Barn Scar headland

is fronted by natural boulder deposits that affords some coastal protection; and the Drigg promontory is a till cliff with gravel spit in the south, overlain by sand dunes.

Figure 4.1: Features of the West Cumbrian coast near the LLWR within the portion of interest of Sediment Sub-cell 11d, extending from St Bees Head in the north to the Ravenglass Estuary in the south

Erosion processes and sediment supply

The size of sediments influences how readily they are entrained and transported in the coastal environment, and where they will ultimately be deposited. Coarse sediment, such as gravel and cobbles, can only be transported by the most energetic waves, which can move the material across the upper beach. Boulder-sized material released by erosion of the cliffs is immobile and forms intertidal lag deposits known as scars, which can provide protection against erosion. In contrast, sand, silt and clay-sized materials are more easily moved by waves and tidal currents. Sand is transported across the lower beach and nearshore zone and where conditions permit, can be blown inland to form dunes. Silt and clay can be transported by weak tidal currents and is generally drawn offshore to the bed of the Irish Sea, with small amounts being deposited in estuaries on mudflats or saltmarsh.

Along the Cumbrian coast, sediment is predominantly supplied to the coast through the erosion of cliffs. As recession of the cliffs progresses, eroded material (cobbles, gravel, sand and fines) is supplied to the foreshore, where it is sorted and redistributed. This sediment budget is a fundamental control on shoreline processes, coastal orientation, cross-shore profile and vulnerability to transgression or accretion. However, the widespread presence of coastal defences reduces the length of cliff line that is actively supplying sediment. Furthermore, glacial sediments forming the cliffs are dominated by silt and clay such that coarse sand, gravel and cobble-sized material for beach-building is in short supply. The relationship between sediment supply, beach volume and erosion rate is a fundamental control on coastal evolution. Erosion of cliffs rich in coarse sediment will tend to cause beach accretion that will absorb more wave energy and lead to a reduction in cliff recession rate. Conversely, erosion of cliffs rich in fine-grained sediment will not accrete a beach, and erosion will continue.

Eroded material behaves broadly as follows:

- sediments classed as fines (i.e. silt and clay) are relatively rapidly transported away from the shore by wave action and regionally by tides (in the case of the LLWR, transport is minimal and in a northern or southern direction, as discussed in Subsection 4.2.4);
- sand forms a highly dynamic lower beach below mean high water;
- gravel accumulates in a less dynamic upper beach above mean high water; and
- cobbles and boulders, which are of limited mobility, are exposed as broad ‘scars’ across the intertidal zone.

Beach characteristics

The characteristics of beaches local to the LLWR site, and in particular sediment particle size distributions, provide important evidence to support the development of conceptual models of beach erosion and cliff recession.

The beaches are characterised by distinctly different upper and lower foreshores, shown in the schematic in Figure 4.2. The term ‘upper foreshore’ refers to the steeper-angled part of the beach that is formed as gravel above the mean high water level. The upper foreshore is also known as the ‘storm beach’ or ‘back beach’. ‘Lower foreshore’ refers to the flatter beach zone between mean high water and mean low water levels and is composed of finer sediments than those on the upper foreshore. The lower foreshore in West Cumbria is characterised by occasional outcrops of gravel and cobbles known as ‘scars’ that represent immobile lag deposits formed by preferential erosion of finer sediment

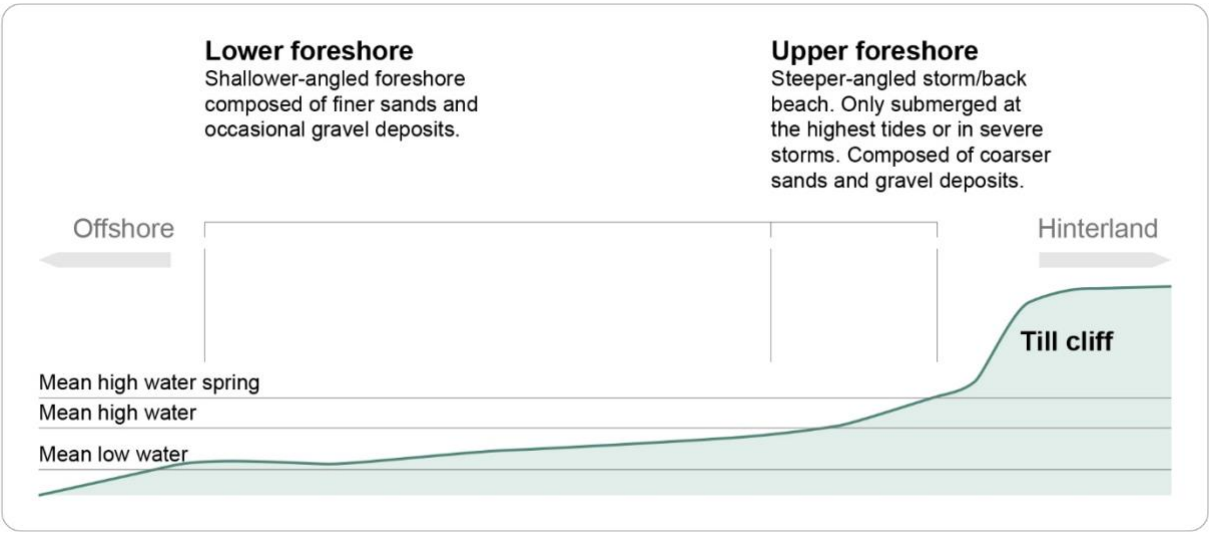

Figure 4.2: Schematic of coastal geomorphology typical of the West Cumbrian coast near the LLWR site

These typical features are illustrated in the photograph of Drigg beach shown in Figure 4.3, which shows the following features (from left to right):

- the sandy lower foreshore, including a boulder lag deposit (known locally as a scar) with green algal/seaweed cover;
- a higher gradient gravel/cobble storm beach (note vegetation cover indicating infrequent impact from waves);
- the till cliff, including slumped vegetation.

Figure 4.3: Photograph of Drigg Beach, illustrating typical features of beaches along the West Cumbrian coast near the LLWR site

Variability in beach characteristics

The nature of the foreshore varies along the coastline, with a general north to south pattern of increasing sand content. In general, storm beaches in the south are less steep and less gravelly than those in the north; Drigg Dunes, for instance, are almost completely formed of sand,

except for thin gravelly sand deposits at the back of the beaches. The higher proportions of gravel to the north of the region can be explained by:

- greater proportions of gravel being contained within the northerly till cliffs and more extensive erosion at these landforms, leading to a greater volume of gravel supply;
- the southerly drift of mobile sand-sized sediment driven by wind, such that sand has been preferentially transported from the north.

In addition to the southerly drift of sand-sized sediment, the increase in sand towards the south can also be explained as resulting from:

- increases in the proportion of sand within southerly till deposits, such that more sand has been available for deposition upon erosion;
- a past onshore supply of sediment, which has led to a concentration of sand within more sheltered estuary areas such as around Ravenglass;
- a historical reduction in longshore transport of sand and hence its deposition due to changes in shoreline orientation; and
- trapping of sand upstream of the Ravenglass Estuary due to the hydraulic effects of the estuary delta.

Upper foreshores in the north are typically relatively steep, and comprise gravel with occasional boulders, while the lower foreshores are flatter and sandy with occasional gravel lag deposits. Where gravel lag deposits are present on the lower foreshore, they are less well sorted and less well rounded than the material on the upper foreshores. This suggests the two bodies of gravel are formed through different processes.

The southern beaches, from Seascale to Drigg Point, are dominated by sand, with decreased concentrations of gravel and shallower angles observed in the upper foreshore compared to the north. As in the north, lower foreshores are wide and sandy with common outcrops of gravel lags. The foreshore at Barn Scar is the most extensive and complex example of a gravel lag deposit and is characterised by till and peat deposits that are occasionally exposed between migrating sand bars. A schematic of the processes associated with the above conceptual understanding of beach and scar development is presented in Figure 4.4.

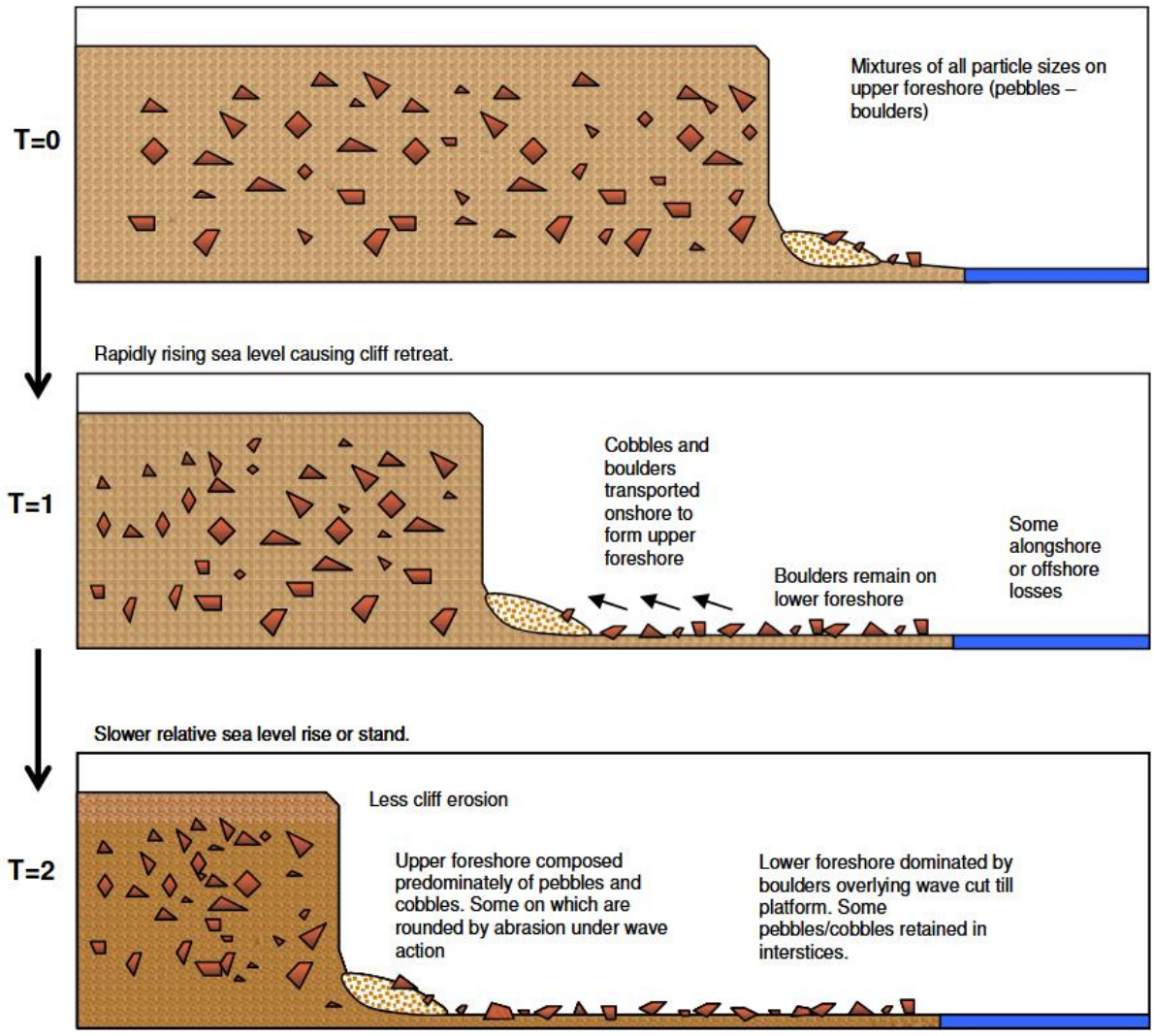

Figure 4.4: A schematic illustrating beach evolution

Estuary system and controls

The Ravenglass Estuary, formed by the combined outlet of the Esk, Irt and Mite rivers, lies approximately 4 km south of the LLWR site. Owing to this proximity, its evolution warrants consideration as to whether it could influence site disruption.

The morphology of estuaries is influenced by three main controls: tides, wave action and river discharges. Characterisation of their behaviour is further complicated by the mutual interaction of these factors. An underlying principle of estuary geomorphology is that tidal power is a function of tidal volume, and the tidal volume increases with the cube of channel length. If the channel section is oversized, velocity is reduced and depth increased, resulting in sediment deposition such that the channel size (i.e. cross section area) decreases. If the channel is undersized, erosion increases the cross-sectional area until the estuary achieves equilibrium. Alternatively, if the tidal power of an estuary is insufficient to allow channel adjustments to be

made, processes such as meandering and increased rates of channel widening in the seaward direction can occur.

The Ravenglass Estuary exhibits all of these responses. The Mite, Irt and Esk rivers all form tidal meanders and in addition, sections of the Esk and Irt run parallel to the shore to increase their tidal lengths. The three river mouths also widen rapidly towards the sea and, once they coalesce, the width of the combined channel increases leading to the formation of a large tidal pond or lagoon. These observations mean that if any of the controlling factors change, for example in response to sea-level change, there will be a corresponding response by the estuary to re-establish a state of equilibrium. However, the Ravenglass Estuary's constituent rivers flow across a steep hinterland, which reduces the available tidal power of the system to cause erosion and limits potential tidal intrusion in response to sea-level rise.

4.2.4 Sediment Transport

Regional sediment cells

Sediment transport typically occurs within distinct sediment cells, which are defined by sediment transport barriers, such as major headlands or estuaries.

The coastline in the vicinity of the LLWR lies within Sediment Sub-cell 11d, which extends from St Bees Head, which is a major barrier to longshore sediment transport northwards, to Hodbarrow Point, which prevents substantial sediment movement southwards. In between lies the Ravenglass Estuary, situated approximately 4 km south of the LLWR, which provides a partial barrier to southwards longshore sediment transport. Thus, for the purposes of modelling and other analyses undertaken for the LLWR ESC, a further refinement of Sediment Sub-cell 11d has been utilised, bounded by the Ravenglass Estuary in the south and St Bees Head in the north.

Regional sediment transport

Erosion of the cliffs formed in glacial sediment and of beach deposits along the Cumbrian coast provide the main supply of sediment available for transport, ranging from muds to boulders. Wave action, storms and tidal flows are the main drivers of sediment transport in the vicinity of the LLWR (characterised in Subsection 4.2.5), with features such as headlands and scars acting as partial barriers. Coarse sediments are transported along the beach by wave action and storm surges, while finer sediments in suspension are transported by tidal flows.

The coastline in Sediment Sub-cell 11d lies almost normal to the dominant wave direction This means that sediment transport on beaches is minimised and there is no net direction of transport along the coast between St Bees and Drigg. At a local level, the direction and amount of beach sediment transport is variable, and sensitive to subtle changes in shoreline alignment at headlands and bays. Modelling demonstrates that wave action typically results in the transport of larger sediments exceeding 2 mm in size, with storm surges capable of moving clasts of up to 76 cm [25].

Finer sediments including muds and fine sands are transported in suspension by tidal currents. Currents flow northwards on the flood tide and to the south on the ebb. There is net northwards direction, supported by evidence of particle movements at Sellafield [46]. Importantly, this means that tidal flows do not drive sediment onshore.

4.2.5 Tides, Waves and Storm Surges

Waves, storm surges and tidal flows are the main drivers of erosion and sediment transport in the vicinity of the LLWR, so understanding their nature is key to understanding the evolution of the surrounding coastline.

Tides

Tidal water levels are obtained from the UK Hydrographic Office [47] for Tarn Point, which provides the closest data set to the LLWR site. The spring tidal range (the maximum variation in water level in a tidal cycle) is 7.4 m. Values for mean sea level (MSL), mean high and low water spring (MHWS and MLWS) tides, and highest and lowest astronomical tides (HAT and LAT, the highest or lowest levels that can be expected to result from average meteorological conditions and any astronomical configuration) are presented in Table 4.1.

Tidal currents tend to flow parallel to the shore, northwards in flood and southwards in ebb. Nearshore currents tend to peak close to high and low water and range from around 0.15 to 0.5 m s^{-1}, enabling the transport of fine-grained sediment only.

Table 4.1: Tidal levels for Tarn Point, the closest data set to the LLWR site [47], converted to m OD

	m OD
Highest Astronomical Tide (HAT)	5.1
Mean High Water Spring (MHWS)	4.1
Mean Sea Level (MSL)	0.3
Mean Low Water Spring (MLWS)	-3.3
Lowest Astronomical Tide (LAT)	-4.1

Waves

Waves are important in the transport of coarse sediment on the beach, and in the entrainment of fine sediment offshore. Along the portion of the Cumbrian coast of interest, waves approach perpendicular to the shore, predominantly from the south-west and occasionally from the north-west. This limits the littoral transport of sediment. Modelling suggests that there is little diffraction of waves along much of the shoreline due to the parallel, uniform nature of the

seabed [48], except for gravel lags ('scars'), such as Barn Scar, where wave diffraction occurs causing localised impacts on sediment transport and thus shoreline morphology.

Approaching the shoreline, waves are depth-limited by shallow gradient bathymetry, which causes waves to build in height before land is reached. However, high spring tides or storm surges result in greater water depths, allowing larger waves to periodically reach the shoreline where they can move larger sized sediment and/or erode the cliffs.

Storm surges

The combined effect of astronomical tides and storm surges result in extreme water levels. It is likely that contemporary storm surges, together with typical waves, have been responsible for generating ‘raised’ depositional features along the coast, such as the gravel ridges south of the Drigg promontory and high elevation beaches such as those beneath beach front properties at Nethertown and Coulderton. An analysis of extreme water levels carried out by the Environment Agency [49] studied the combined impact of a storm surge and the MHWS tides and estimated that extreme water levels near Drigg were 5.5 m OD and 6.3 m OD for periods of 5 years and 1,000 years, respectively. Furthermore, the additional impact of waves breaking on the shore means erosion will occur at elevations several metres above the quoted extreme water levels.

4.2.6 Summary of Present-day Coastal System

This subsection draws together the main outputs of the above discussion to summarise the conceptual understanding of the contemporary system, and thus the baseline for projections of future coastal development.

Sediment supply and transport

Coastal evolution around the LLWR site is driven by erosion and sedimentation processes that form a variety of coastal features and lead to both coastal recession and accretion at low rates, based on historical data.

Erosion of cliffs along the Cumbrian coast provides the main source of sediment supply in the form of silt, sand, gravel and cobbles, although actual supply is reduced by the presence of coastal defences and shore platforms that inhibit coastal erosion. Coarse sediments are transported along the beach by wave action and storm surges, while finer sediments in suspension are transported by tidal flows. There is limited net direction to the movement of sediment, with material able to move both north and south with the sediment cell defined by St Bees Head and the Ravenglass Estuary.

Coastal geomorphology

The coastline in the vicinity of the LLWR is characterised by extensive sandy intertidal flats, shingle ridges, and dune systems punctuated by a series of rivers and estuaries. Closest to the LLWR site there are episodically eroding cliffs at Carl Crag, the headland at Barn Scar.

Beaches local to the LLWR site are characterised by distinct upper and lower parts:

- Lower beach: A gently sloping zone between mean high and low water that is composed of highly mobile sand. Cobble and boulder lag deposits are sometimes present on the lower beach.
- Upper beach: A steeper-angled portion of the beach that is only submerged by particularly high tides and storm surges, composed of coarser gravel deposits.

Variability in foreshore characteristics is observed along the coastline owing to a general north to south pattern of increasing sand content. Upper foreshores in the north are typically steeper and comprise coarser material than those in the south, which are dominated by sand.

To the south of the LLWR site, the combined outlets of the Mite, Irt and Esk rivers forms the Ravenglass Estuary. The large tidal lagoon presents a significant sink of sand along the stretch of coastline of interest. Its morphology is controlled by tides, wave action and river discharges. These are susceptible to change in response to sea-level rise, although potential tidal intrusion is limited by the steep hinterland over which the constituent rivers flow.

4.3 Projections of Coastal Landscape Change

We have used several modelling approaches, to project future coastal landscape changes. These approaches are informed by the climate projections (Subsection 3.6) and the coastal conceptual model (Subsection 4.2). In this Subsection, an overview of the approaches is presented in Subsection 4.3.4, followed by a summary of the projected coastal erosion to initial site disruption (i.e. at the time when the LLWR is first exposed) in Subsection 4.3.6. An overview of the projected evolution of the Ravenglass Estuary over the timescales to initial site disruption is provided in Subsection 4.3.7. Finally, a summary of the projected coastal erosion to complete site erosion is presented in Subsection 4.3.8.

4.3.1 Location and Elevation of the LLWR

Distances between the repository and current coast, and elevations of the repository are presented in Figure 4.4.

Two south-west to north-east sections dissecting the northwestern part of the LLWR are used in the coastal landscape projection models (Figure 4.5). Carl Crag South (Line C) runs from the coast to and along the northwestern boundary of the LLWR. The section represents the shortest distance between the coast (measured from the cliffline) and the LLWR vaults, which is approximately 350 m. Carl Crag North (Line D) runs from the coast to and across the northwestern area of the LLWR. The distance between the coast and vaults is approximately 450 m along this section. Additional section lines, which run south-west to north-east across the middle of the repository at Barn Scar and to the south/south-east at Drigg Dunes, are also considered in the modelling.

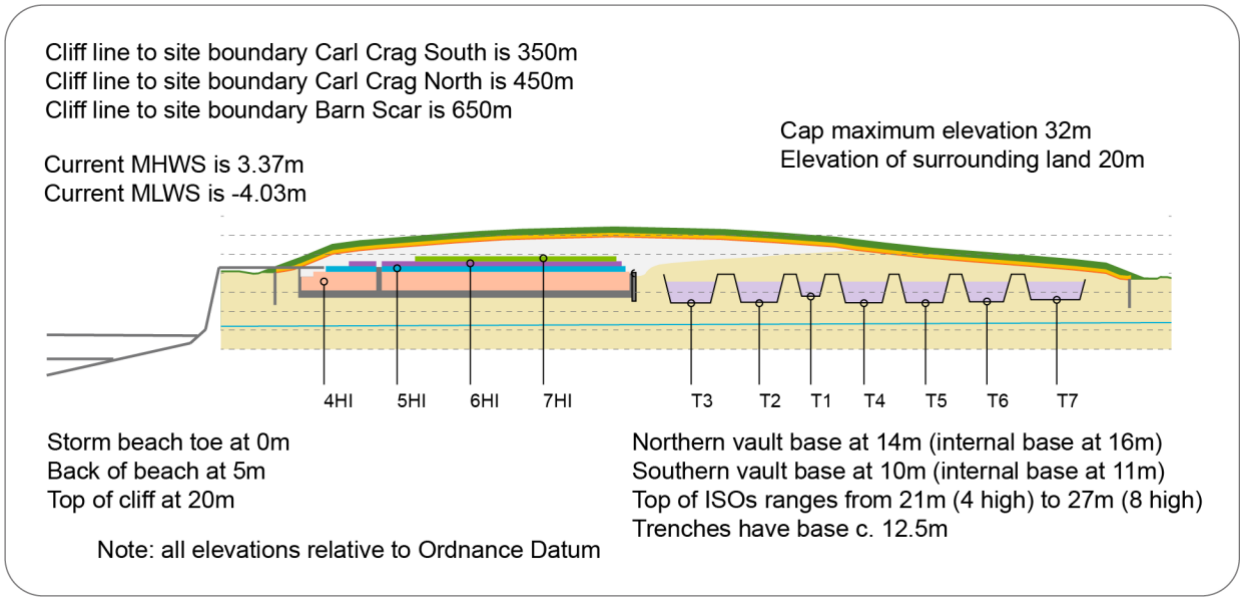

Figure 4.4: Schematic representation of the distances between the LLWR boundary and the current coast, and the elevations of key features of the repository (in metres relative to OD)

Figure 4.5: Map of the LLWR showing the location of profiles used in the coastal landscape modelling

4.3.2 Basis for the Projection of Future Coastal Change

4.3.2.1 Sea-level Rise

Sea-level rise is the primary driver of coastal erosion at the LLWR. The ranges presented in Table 3.6 and illustrated in Figure 3.9 are used in the projections of coastal erosion.

4.3.2.2 Potential for Future Changes to Local Coastal Processes

The beaches near Drigg are not currently dependent on sediment supply from outside of its sediment cell (Subsection 4.2.4). However, large-scale changes in processes that influence the West Cumbrian coast could bring about different processes and change the evolutionary trend of the shoreline. The types of changes that would be required include, for example, changes in the dominant wave direction to trigger changes in the sediment transport directions or significant coastal erosion in adjacent areas of Morecambe Bay or St Bees Head that currently act as major controls on regional sediment budgets.

The shoreline is heavily influenced by sediment transport under storm conditions. It is possible that a change in the storm tracks across the Irish Sea, triggered by millennial-scale climate changes similar to those seen in the Lateglacial [50] could result in a change in incoming wave direction, leading to a stronger or more dominant alongshore sediment transport system. However, there is very little evidence that the wave regime would be so modified, or that future climate change will lead to significant changes to tidal ranges, storm surge levels or waves. This is because the system is essentially self-contained and the wave regime is geometrically constrained; future changes to the coastline are unlikely to be sufficient to challenge this control. Overall, based on available evidence it is considered unlikely that a sufficiently large-scale change will occur over the next thousand years [51], which is similar to the projected timescales for erosion.

4.3.2.3 Future Estuarine Development

Sea-level rise and sediment supply influence the geomorphology of the Ravenglass Estuary and future coastal landscape change. If sufficient sediment is available to keep up with sea-level rise, deposition occurs on the bed and banks of the estuary channel and its channel dimensions are constant. In this scenario, the hinterland could be buried by the deposited sediment. However, if the sediment supply is insufficient to keep up rising sea level, the channel dimensions increase, which could cause hinterland erosion.

Additionally, an increase in the intensity of rainfall events leading to higher flows in the rivers Irt, Mite and Esk, could periodically destabilise the mouth of the Ravenglass Estuary leading to changes in its morphology. However, geophysical surveys have suggested that the northern portion of the Drigg Spit is underlain by glacial till, meaning the potential for estuary mouth change is spatially limited [52].

4.3.2.4 Resistance to Erosion and Future Sediment Supply

The shoreline's resistance to erosion is an important consideration for prediction of future coastal change. Resistance has been assessed through studies concerning the depth and spatial extent of the underlying bedrock surface. Relevant data show that the Permo-Triassic sandstone bedrock cliffs at St Bees Head are resistant to change, and that for the majority of the rest of the coastline the bedrock surface is below OD and does not influence present day erosion. The LLWR itself lies on the boundary of an over deepened trough, with bedrock rising from circa 30 m below OD in the southeastern part of the site to OD in the northeastern corner. Bedrock is therefore too deep to influence coastal change at the LLWR.

The hinterland cliffs and sediments directly underlying the LLWR are composed of Quaternary glacial till. Variations in these sediments also exerts a control on shoreline resistance to change. For example, coarse glacial outwash boulder deposits (as exposed at Nethertown headland) are more resistant to erosion than the fine-grained tills exposed at Carl Crag and Drigg [53].

Sediment is supplied to beaches from the erosion of cliffs along the Cumbrian coast (Subsection 4.2.4). The nature of the Quaternary sediments exposed in the cliffs and hinterland is also a fundamental part of conceptual models for the future development of the coastline because it determines the volume of coarse beach-building sediment that will be supplied in the future.

The future sediment supply from the coastline features associated with Carl Crag, Barn Scar and the Drigg Coast SSSI areas is estimated from geophysical surveys and pre-existing borehole data [52]. The volumes of gravel, sand and fines released per metre of cliff recession have been calculated in reference [51].

- In general, to the north of the facility (i.e. from the Carl Crag area) there is a moderate proportion of gravel, which initially increases with distance inland from the current cliff before decreasing from a few hundred metres inland. The proportion of sand increases very slightly with distance inland, and on average is slightly higher than that gravel supply.
- At the Barn Scar section of the coastline, a generally low occurrence of gravel is predicted, increasing after 500 m inland. There is a moderate to high proportion of sand, which peaks at 550 m from the current cliff position. The fines supply is moderate.
- The proportion of gravel, sand and fines is variable in the area of the Drigg promontory to the south of the facility. The gravel occurrence is generally low, and absent between 750 and 1,650 m from the current cliff. The supply of sand is moderate, except for the region between 1,250 and 1,500 m inland where it is lower. There is also a moderate proportion of fines from this section, which remains fairly constant with distance from the current cliff position.

4.3.3 Hinterland Erosion Projections in the 2011 ESC

Two different numerical modelling approaches were used to model cliff recession and hinterland erosion in support of the 2011 ESC; (empirical Coastal Recession Modelling (CRM) and process-based Soft Cliff and Platform Erosion (SCAPE) modelling) [34]. The two approaches help to characterise the projections within appropriate ranges, rather than providing specific predictions.

The CRM simulates the feedback between cliff recession, the sediment being eroded from the cliff, the growth of the gravel storm beach at the cliff foot, and sea-level rise. Relative sea-level rise is expected to result in increased wave attack at the shoreline, promoting cliff recession. This will result in more rapid gravel supply to the storm beach, increased protection of the cliff base and, therefore, a reduction in recession. The CRM is underpinned by empirical relationships between 1) relative sea-level rise and recession rates, and 2) beach volume and recession rate, and considers the beach sediment budget. The inputs to the model comprise volumes of differently sized sediment released by cliff recession, a sediment budget that defines annual losses offshore, alongshore or resulting from clast attrition, and rates of sea-level rise.

SCAPE is a system of process-based modules (e.g. platform, cliff, beach and hydrodynamic load) that simulate wave transformation, tidal fluctuation, sea-level rise, erosion in the littoral zone and the protective effect of the beach. The model reshapes the whole shore profile at each time step, considering the erosive potential across the shore zone. The shore gradient is important feedback in the model; higher erosion leads to a flatter platform profile resulting in greater wave dissipation and lower erosion. The size of the beach and its protective effect on the platform are also considered in the SCAPE model. The model was refined to reflect site-specific conditions near the LLWR, including foreshore boulder lags, and was calibrated using hindcasting informed by historical cliff recession rates derived from the conceptual model

The CRM and SCAPE model considered the low and high sea-level scenarios that were used to underpin the 2011 ESC. The model results were compared to critical recession distances (e.g. in Subsection 4.3.1), which are the distances to the LLWR site boundary from the coast at different representative positions along the coast. This comparison provided estimates of the time at which the LLWR would be first disrupted by cliff recession. In the CRM, site disruption was estimated at around 400 to 800 years AP. In the SCAPE model, site disruption was similarly estimated at around 300 to 900 years AP [34].

4.3.4 Hinterland Erosion Modelling Approaches

The 2026 ESC adopts a similar approach as the 2011 ESC, which is to investigate the range of potential outcomes rather than providing a specific prediction based on a single case.

In 2017, we undertook a review of erosion modelling approaches and developments in coastal science. This concluded that that CRM and SCAPE continue to be effective tools for modelling the West Cumbrian coast [45]. This is illustrated by the Environment Agency's use of bespoke SCAPE models in their 2024 update of the National Coastal Erosion Risk Mapping project,

which aims to highlights areas at risk of coastal erosion [54] [55]. We recognise that the timescales considered in the ESC are far greater than those typically considered when modelling is undertaken to support decisions about coastal management. Coastal erosion modelling over long timescales is not routine and limited capability exists. Additionally, the long timescales introduce uncertainties that can lead to model projections increasingly deviating from the actual system behaviour. The correlation between coastal recession and projected future rates of sea-level rise lacks validation, as comparable rates of sea-level rise have not been observed within recent historical records.

To help address the uncertainties and improve our understanding of coastal recession, the 2026 ESC assesses the timescale for exposure of the LLWR frontage using updated coastal recession and SCAPE models, as well as two supplementary methods. The updated CRM and SCAPE models reflect the refined sea-level rise scenarios (Subsection 3.6). The CRM also is underpinned by more recent coastal monitoring data to better represent the sediment budget of the coastal system.

In addition to these numerical approaches, we have also used two simpler methods:

- the Bruun rule, which is an equation that relates sea-level rise to cliff recession based on the assumption of an equilibrium shore profile; and
- the extrapolation of historical cliff recession rates at Drigg Beach.

A review of these simpler coastal erosion projection methods concluded that they could provide useful projections up to a few hundred years where rates of sea-level rise are low. These approaches were not used as heavily in the 2011 ESC because they were not considered to be relevant to the projected rates of sea-level rise adopted at the time. However, they are considered relevant to low sea-level rise projections in the 2026 ESC, as the rates of sea-level rise for this projection are similar to those of the historical period.

4.3.5 Hinterland Erosion Projections

4.3.5.1 Extrapolation of Historical Cliff Recession Rates

A simple method of projecting future cliff recession rates is to extrapolate historical rates. Historical rates have been estimated at Carl Crag and Barn Scar by mapping coastal features and measuring changes over time using [24, 52]:

- georeferenced OS maps (1840s to 2002);
- aerial photographs (1940s to 2009); and
- light detection and ranging (LiDAR) data (2002 to 2020).

This analysis suggests that the long-term historical cliff recession rates since the 1840s were 0.25 m y^{-1} at Carl Crag, and 0.1 m y^{-1} at Barn Scar. Higher rates of change were observed in short-term LiDAR datasets that record the impact of high magnitude, low frequency events.

However, these rates are smoothed out in longer-term records and are therefore not considered representative [25].

This approach is considered appropriate when future sea-level rise is similar to those of the historical period. However, historical erosion rates may have been influenced by defences and railway embankments that have reduced sediment supply since the 1840s. If these defences and embankments are abandoned in the future, increasing sediment supply, then future erosion rates could be less than the historical rates, assuming the rate of sea-level rise is the same as the historical rate [25].

4.3.5.2 Bruun Rule

The Bruun rule is a simple geometrical equation that quantifies future recession rates based on the assumption that the profile remains in equilibrium [56, 57]. The Bruun rule describes a linear connection between sea-level rise and shoreline recession, based on the idea that the shore face aims to keep its equilibrium profile. As sea level rises, the profile shifts landward and upward, eroding the upper beach and depositing material offshore to maintain constant water depth.

It can only be reliably applied to sand-based coastal morphologies with sand-based foreshore and nearshore bathymetry. It makes no compensation for gravel behaviour on the shoreline, nor provides any geological control on offshore bathymetry. Such aspects are components of the SCAPE model.

Although widely used, the Bruun rule is only scientifically credible as a 1st order approximation, which generally gives estimates of the recession rate that are too high [57].

The inputs to the Bruun rule equation, which are quantified based on coastal monitoring data, published literature, 2026 ESC sea-level change projections (Subsection 3.6), coastal observations and the geological model, are [25]:

- historical recession rates;
- historical rates of sea-level rise;
- future rates of sea-level rise;
- a simplified platform geometry; and
- the proportion of cliff sediments that remain on the profile.

4.3.5.3 Coastal Recession Modelling

The CRM estimates the cumulative recession rate of a cliff-beach profile over time, considering relative sea-level projections and beach sediment budget. It represents the feedback between cliff recession, the sediment being eroded from the cliff and the growth of the gravel storm beach at the cliff foot. Relative sea-level rise is expected to result in increased wave attack at the shoreline, promoting accelerated beach removal and cliff recession. This will result in more rapid gravel supply to the storm beach and increased beach volume, which protects the base of

the cliff and reduces recession. The CRM is based on empirical relationships that reflect this feedback. These relationships are between 1) relative sea-level rise and recession rate, and 2) beach volume and recession rate.

It models cumulative recession by modifying an initial recession rate (i.e. at time = 0 years) based on the empirical relationships to estimate a new recession rate (i.e. at time = year 1). The new recession rate changes the beach sediment budget, specifically the gravel supply and beach volume. The change in beach sediment budget and the subsequent relative sea-level rise result in a new updated recession rate (i.e. at time = year 2), and so on.

Figure 4.6 shows an influence diagram summarising the relationships between the main elements of the model:

- relationships are negative if an increase in one factor leads to a reduction in the other;
- relationships are positive if an increase in one factor leads to an increase in the other.

Beach volume is at the centre of the model and has a direct negative impact on recession rate. Beach volume is, however, variable over time and is a function of the balance between sediment inputs (from cliff recession; positive) and the outputs from 'beach erosion and attrition' (negative).

As beach volume rises, sediment input falls due to its impact on the recession rate, while sediment output grows and reduces beach volume. A fixed percentage of this volume is lost annually, based on model hindcasting over the past 20 years.

As beach volume decreases sediment input increases because of the effect on recession rate, but sediment output also decreases. This provides a 'self-regulating' mechanism that controls beach volume and, hence, recession rate.

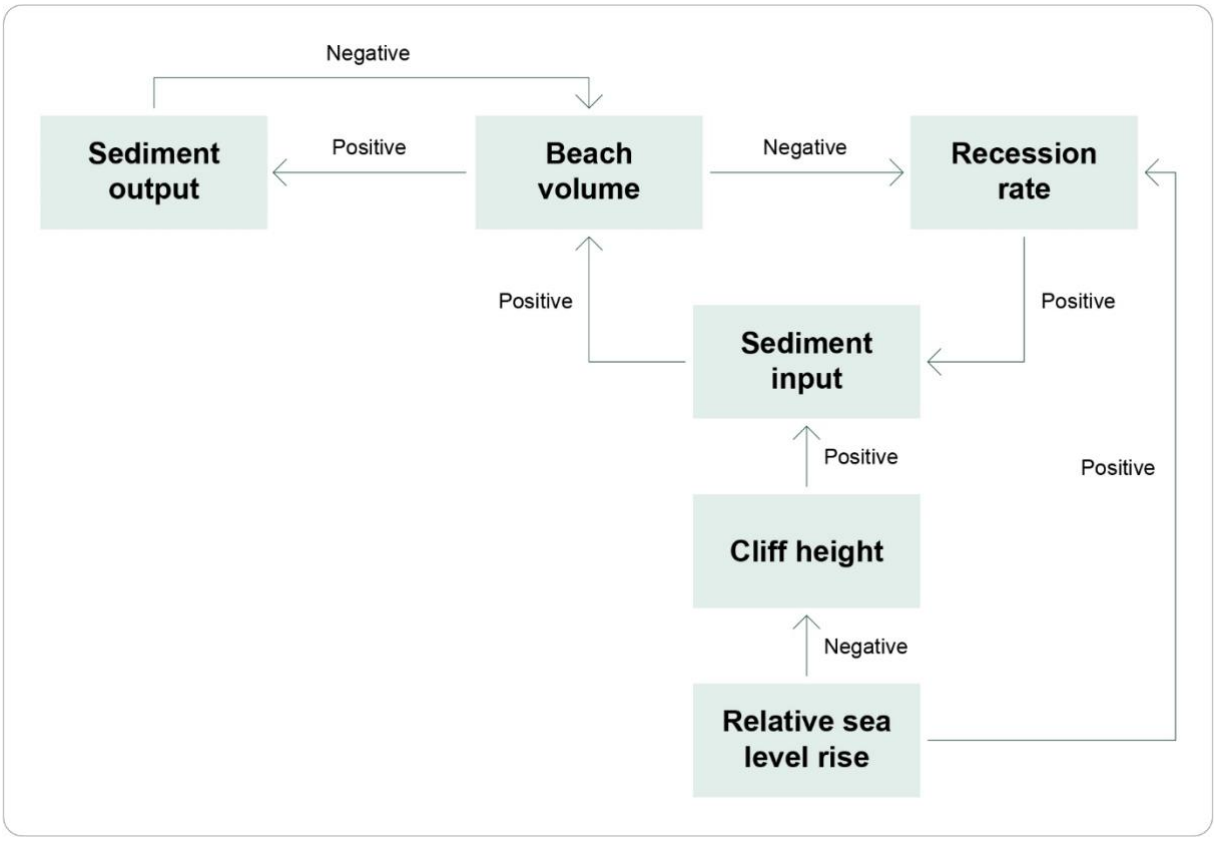

Figure 4.6: Influence Diagram for the Cliff Recession Model

CRM empirical relationships

Relative sea level and recession data from the glacial sediment cliffs (between Hornsea and Withernsea in the East Riding of Yorkshire, and between Kessingland and Southwold in Suffolk) provide more than one hundred years of representative analogue information. These long-term data have been used to develop an empirical relationship between recession rate and relative sea-level rise for West Cumbrian cliffs for use in CRM [25].

This relationship states that for 1 mm of relative sea-level rise, there is a 1% increase in recession rate, and there is a linear relationship between the recession rate and relative sea-level rise. The sea-level projections, illustrated in Figure 3.9 (Subsection 3.6), are used in this empirical relationship to inform the erosion rates in the CRM.

Cliff recession reflects the balance between the strength of the materials that comprise the cliff and the stresses imposed on the cliff by gravity and kinetic energy (e.g. waves). Erosion and cliff recession occur when tidal elevation and wave run-up elevation exceed the elevation of the base of the cliff. Wave characteristics and the beach morphology control the wave run-up elevation. In particular, the size of the storm beach and its slope, as well as the talus at the foot of the cliff impact wave run-up. The larger the storm beach and talus and lower the slope, the greater protection its provides and lower the recession rate. Analogue data from the glacial sediment cliffs of Suffolk and Norfolk show a general trend of decreasing storm beach size and increasing recession rate [25, 58].

Recent beach monitoring and cliff recession data in the vicinity of LLWR show that where the storm beach exceeds 80 m^2 m^{-1}, cliff recession rates of <0.2 m y^{-1} are typical, whereas highly varied rates ranging from 0 to 1 m y^{-1} or more are recorded if the storm beach is less than 80 m^2 m^{-1}.These observations are used to inform empirical relationships between beach area and recession rates in the CRM for the West Cumbrian cliffs [25].

Impact of beach volume for CRM

Beach volume is a key control on the CRM. It varies over time as a function of the sediment inputs from cliff recession and the outputs from beach erosion, attrition and offshore/alongshore losses. The following assumptions relating to beach volume, which are supported by recent beach monitoring data bathymetry surveys and the LLWR geological model, are used in the CRM [25]:

- beach volume is independent of the rate of relative sea-level rise – the beach migrates onshore as sea level rises;
- sediment input per metre of recession, expressed as proportions of gravel, sand and fines, is a function of cliff height. Cliff height is progressively reduced by relative sea-level rise (unless and until there is a topographic rise inland);
- the sediment input retained on the beach is a fixed proportion of the inputs and independent of the beach volume and rate of relative sea-level rise; and
- the sediment outputs from the beach are proportional to the beach volume and independent of the rate of relative sea-level rise or recession rate.

In relation to the sediment outputs, clast attrition rates applicable for beach environments can only be estimated. They will depend on the lithology of gravels supplied, which is uncertain, but are assumed to be similar to the contemporary beach. Beach monitoring over the last 20 years suggests some fluctuation in the size of beaches due to storms, but no discernible net change [25]. A similar picture is indicated by historical aerial photographs from the 1940s to present day. The sediment output value in the CRM was therefore set to a value that maintained the beach volume for circa 100 years, before effects of sea-level rise or changes in sediment inputs caused a significant influence on the beach.

Limitations of CRM

The projected low rates of erosion mean that the models have been run for much longer than the model is conventionally designed for. Through sensitivity analysis we have shown that uncertainty inherent in the model itself compounds towards lower rates of recession and may be significant [25]. Taking account of extrapolation of historical erosion rates discussed below, we conclude that the CRM overestimates projected timescales to exposure.

4.3.5.4 Soft Cliff And Platform Erosion Modelling

SCAPE is an advanced numerical modelling tool used to describe the erosion of coasts, notably comprising material such as clay, till and soft rock [59, 60]. SCAPE is a process-based model that simulates the removal of in-situ shore profile material by wave action. The two most important feedback processes that regulate model behaviour act to modulate the beach volume and platform profile are:

- Higher coastal retreat → beach growth → greater protection → lower coastal retreat.
- Higher coastal retreat → flatter platform profiles → greater wave dissipation → less platform downwearing → lower coastal retreat.

Typical components of SCAPE system models are shown in Figure 4.7. SCAPE has modules representing the platform, cliff and beach, as well as hydrodynamic loads. Such holistic representation is necessary to capture interaction and feedback that regulates the behaviour of such coasts.

A system of process-based and behavioural modules simulate the impact of wave transformation, tidal fluctuation and sea-level rise on a shore profile, comprising a beach and substrata, over time (Figure 4.8).

The distribution of erosion on the profile is regulated by the changes in its slope and the depth of the beach. Steep platform profiles are prone to higher erosion rates, which reduces the steepness of the profile, resulting in greater wave dissipation and less erosion. If the sea level is constant, the slope steepness and erosion decrease, and the rate of retreat of the platform decreases asymptotically. However, if sea level is rising, the platform will retreat owing to inundation and erosion associated with wave attack. The rate of retreat will equalise across the profile and become constant, resulting in a stable profile shape [59].

The profile shape is also influenced by the beach. The beach has a protective effect on the highest parts of the platform. In lower areas that are seaward of the beach, the platform is not protected and therefore erodes, resulting in a decrease in the platform slope in this location.

The SCAPE model assumes the beach volume is constant because it is two-dimensional and cannot account for changes in the sediment budget relating to longshore sediment inputs and outputs. As sea level rises and erosion proceeds, the beach geometry changes to account for the sediment that is generated by the erosion of the platform seaward of the beach. The beach extends seaward, becoming wider and thinner. Once a minimum beach depth is reached, waves begin eroding the platform under the beach. The profile of the platform under the beach is relatively steep, compared with the seaward locations on the platform, and therefore is prone to higher erosion rates [59].

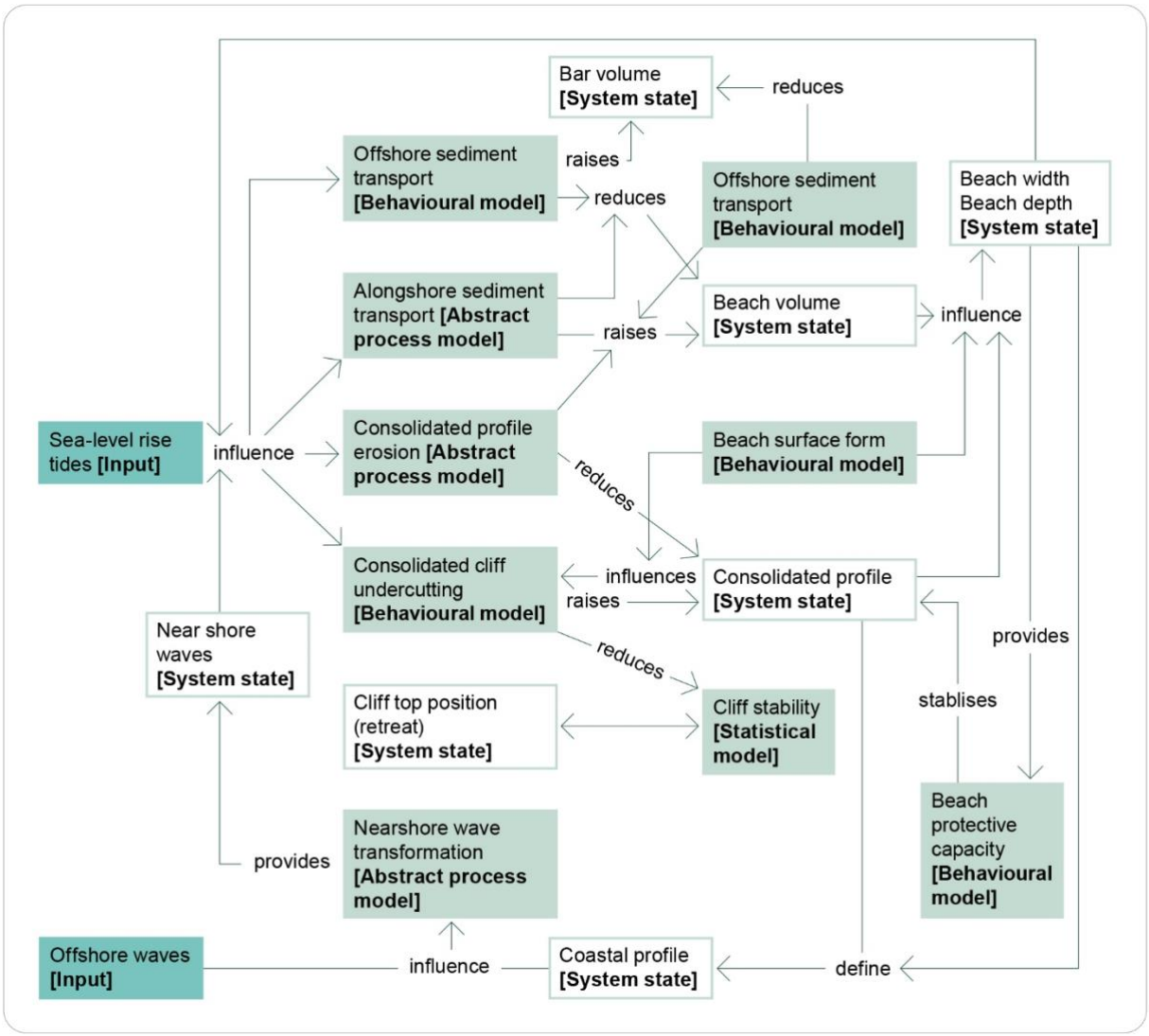

Figure 4.7: SCAPE system map

In the 2011 ESC, a bespoke SCAPE model was developed for the site-specific geomorphology at the LLWR (including the cobble/gravel shore platform that limited erosion on the intertidal part of the shore profile and down-wearing of the profile below mean low water). This model is based on the Carl Crag section.

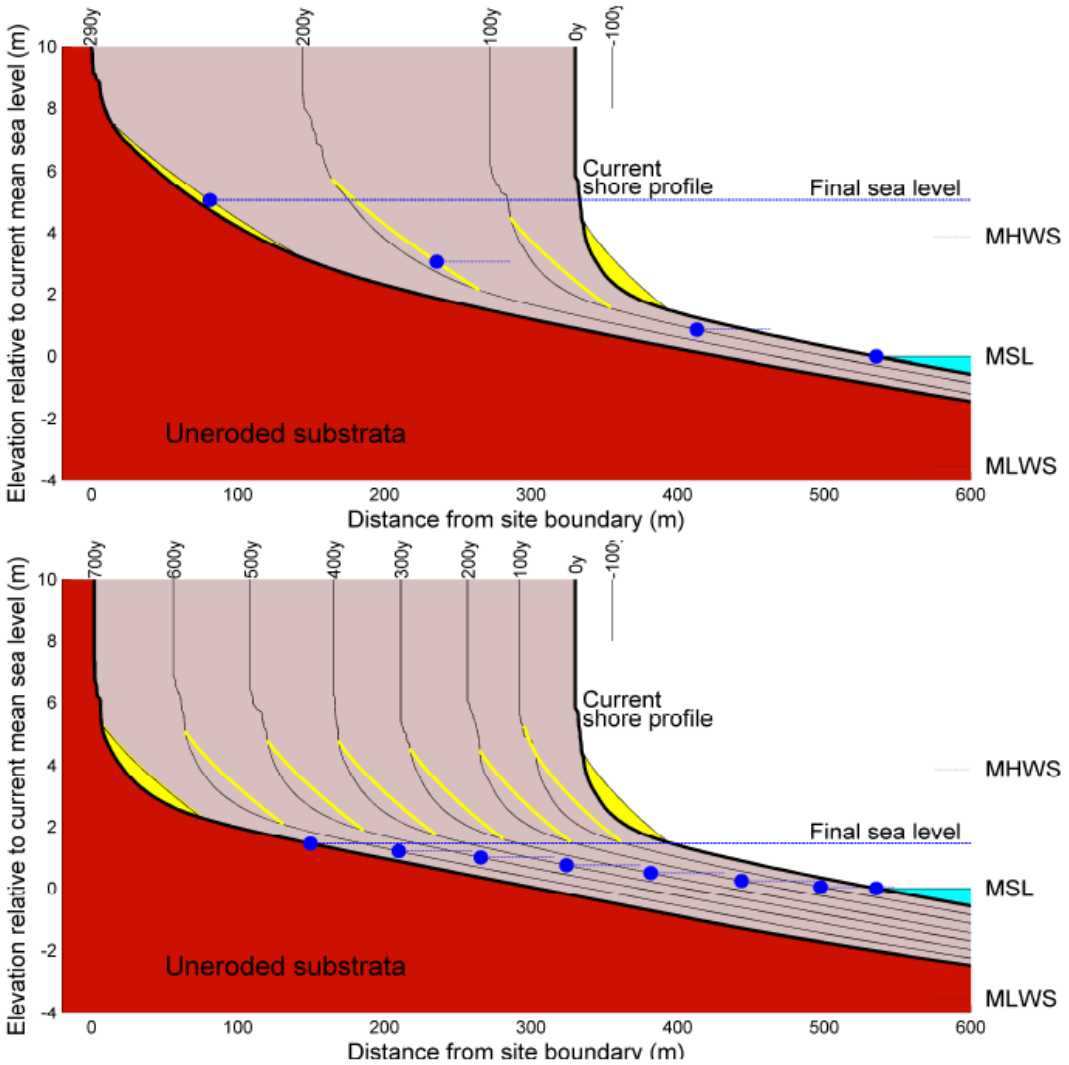

Figure 4.8: **Schematic, illustrative examples of shore profile development with sea-level rise through time from SCAPE. Top: extreme high sea-level rise scenario. Bottom: an extreme low sea-level rise. The beach is shown in yellow and the platform substrata are shown in red. Waves under Mean High Water Spring tides (MHWS), Mean Low Water Spring tides (MLWS) and Mean Sea Level (MSL).**

Prior to modelling the future recession, hindcasting of the model was performed for calibration. Hindcasting was used to develop understanding of the relationship between processes and profile formation and to allow testing and improvement of model performance. It also provided a model version of the current Carl Crag profile, which is required for the forward projections. The hindcasting model was run to represent the period from 11,000 years ago to the present day and was calibrated considering substrata strength and shoreface downwearing rate coefficients, which closely represent the historic recession rate at the Carl Crag location (0.25 m y^{-1}) [61].

Hindcasting is typical in SCAPE model development, although it was exceptionally long in the LLWR model to account for long timeframes over which projections were required. Nonetheless, the modelled shore profile resulting from the hindcasting was a good match with the observed shore profile; the modelled profile was within a metre elevation of the observed profile to around 1.5 km from the shore [61].

The 2011 SCAPE model has been reused in the 2026 ESC, because more recent beach monitoring has reaffirmed the conceptual model. Owing to its strong dependency on sea-level rise, in 2018 the SCAPE model was re-run considering the three revised sea-level scenarios [62]. While these sea-level scenarios are not identical to those in the 2026 ESC (Subsection 3.6), they are very similar and so these 2018 model projections were retained for use in the 2026 ESC.

The SCAPE model also depends on the assumption that the beach volume does not change. However, the beach volume has been shown to vary [25] and will impact erosion as it has a protective effect on the platform. It is assumed in the model that the sediment budget is constant and that the additional sediment generated by recession is transported away.

Importantly, sediment budget is a key sensitivity in the CRM, and therefore this aspect of the coastal geomorphology is reflected in the range of projections of recession.

Limitations of SCAPE

The strength of platform substrata is a key control on the rate of erosion in the SCAPE model. A strength value has been calibrated against a relatively high historical erosion rate, based on observations from 1863 to 2002 at Carl Crag (0.25 m y^{-1}). Using hindcasting, a good match is observed between the current profile and the modelled profile using this historical rate. However, this value is variable in space and time, and lower historic rates have been recorded in other sections along the coast adjacent to LLWR. A lower historic rate in the SCAPE model would provide a higher strength factor, which would result in a lower recession rate, and therefore a longer time to disruption. We therefore conclude that SCAPE may tend to produce higher erosion rates than are expected.

4.3.5.5 Results

Table 4.2 summarises this time for the different approaches, considering the three sea-level change scenarios (outlined in Subsection 3.6).

Table 4.2: Summary of the time to site disruption based on coastal recession projections. The Bruun rule projects erosion rates of 4 m y^{-1}, which are far higher than the historical rates and are not considered credible [25].

Projection approach	Years to initial site disruption (after present)		
	Reference Emissions Scenario	**High Emissions Scenario**	**Low Emissions Scenario**
CRM (Carl Crag C)	1,800	1,500	2,000
CRM (Carl Crag D)	>2,500	2,300	>2,500
SCAPE model (Carl Crag C)	500	350	1,000
Extrapolation of historical cliff recession rates (Carl Crag C)			1,400 to 3,500[b]
Bruun rule			*<100[b]
Expert judgement range[a]	1,000 to 1,500	500 to 1,000	1,500 to 2,000
Recommended assumption for assessment modelling purposes	1,250	750	1,750

[a] Based on the Carl Crag C profile, which represent the shortest distance from the current cliff to the LLWR vaults.

[b] Extrapolation of historical erosion rates is an appropriate approach for the Low Emissions Scenario because the rate of sea-level rise is similar to the historical rate. However, it is not appropriate for the other scenarios, where the projected rates of sea-level rise are significantly greater than those of the historical period.

In general, the modelling approaches used to project coastal recession in the 2026 ESC are subject to uncertainties and limitations, relating to [25]:

- model biases;
- the absence of long-term underpinning empirical data sets;
- the coastal response to a very rapid rise in sea level; and
- compounding of biases and uncertainties over long timescales that can lead to model projections increasingly deviating from the actual system behaviour.

Considering the model uncertainties and limitations, the results of each approach are interpreted to provide estimates as broad ranges [25]. In general, the CRM is considered to be underestimating coastal recession rates and overestimating the time to disruption, owing to the underpinning empirical datasets and compounding of errors when the model is run for very long timescales. However, the results of the CRM are balanced by the SCAPE model, which is interpreted to be overestimating coastal recession rates and underestimating the time to disruption because of model biases.

The results of the extrapolation of historical rates are also considered, but only for the Low Emissions Scenario because this approach is not appropriate for the other scenarios. The lower end of the range is interpreted to be an underestimate because it is based on a high erosion rate (0.25 m y^{-1}), which is not considered to be representative of longer time periods, and the shortest width of hinterland. The upper end of the range is interpreted to be an overestimate because it is based on a low erosion rate (0.1 m y^{-1}) and incorporates protection by lag deposits [25].

By understanding and examining the biases and limitations, and using multiple complimentary methods, we can estimate timescales for initial site disruption expressed as a broad range, accepting and managing the intrinsic uncertainty associated with making such projections. On this basis, the time to first site disruption along the Carl Crag C profile, which is the shortest distance from the current cliffs to the LLWR vaults, is estimated to be (Table 4.2):

- 1,000 to 1,500 years for the Reference Emissions Scenario;
- 500 to 1,000 years for the High Emissions Scenario; and
- 1,500 to 2,000 years for the Low Emissions Scenario.

The improved sea level and sediment budget understanding captured in the refined projections for the 2026 ESC suggest that the site disruption will be later compared with the 2011 ESC (400 to 900 years [34]).

4.3.6 Initial Site Disruption

The sea level at the time when the coast has receded by 350 m (i.e. reached the LLWR vaults) will dictate the mechanism by which the LLWR will be first disrupted. Three mechanisms could cause site disruption. These are:

- undercutting and erosion of the vaults due to cliff recession under conditions of low sea-level rise;
- direct wave loading and erosion of the vaults due to cliff recession under moderate sea-level rise; and
- overtopping and inundation of the vaults due to high sea-level rise (Figure 4.9).

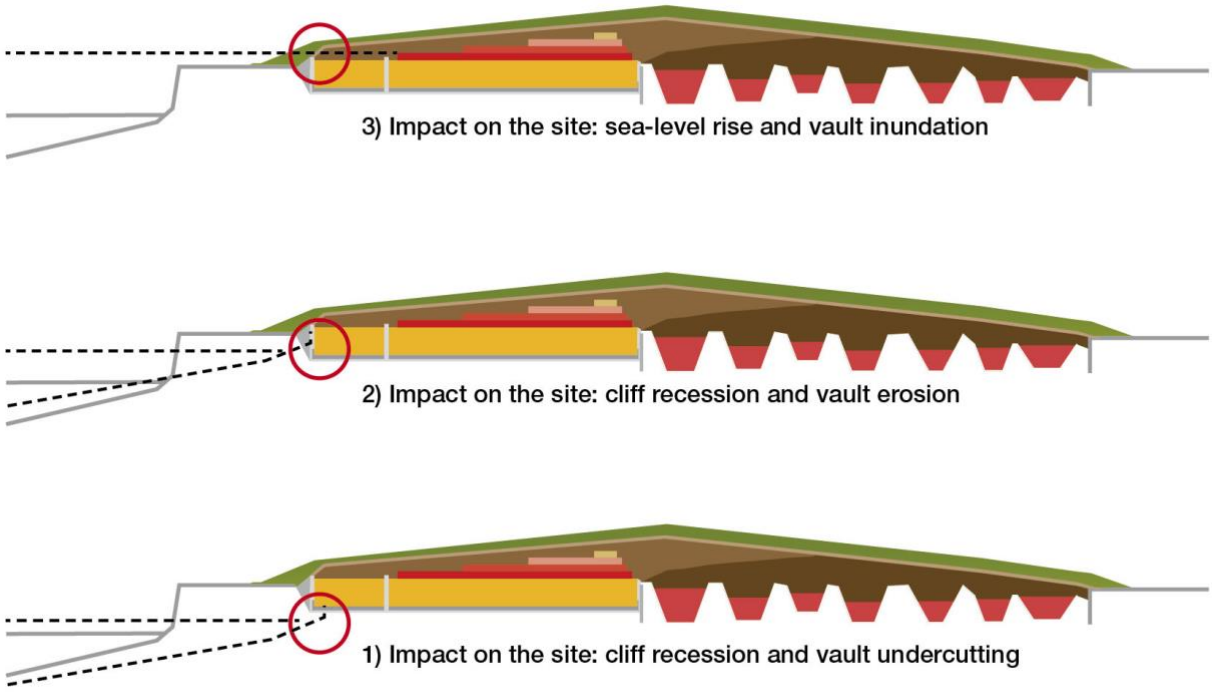

Figure 4.9: Schematic diagram showing the generic processes resulting from coastal recession that could disrupt the LLWR. Future platform geometry and sea level relative to the LLWR are shown in the dashed lines. 1) Vault undercutting, 2) vault erosion and 3) vault inundation.

In the Reference Emissions Scenario, the sea level at the time when coastal recession disrupts the LLWR (1,000 to 1,500 years; Table 4.2) is projected to be 6 m OD, which is below the height of the vaults (Figure 3.9). The projected base of the cliffs, which is 5 m above the sea level (assuming a consistent beach profile) will be below the base of the vaults, and the disruption mechanism will be by vault undercutting. The only possible difference relates to the potential future vaults at the south of the disposal area that are expected to have a base at 10 m OD. For these vaults, failure will be by undercutting over the next 1,200 years, but by direct wave attack in the period beyond 1,200 years, at which time the projected base of the cliff rises above 10 m OD.

Rather than sea level change to base of the cliffs.

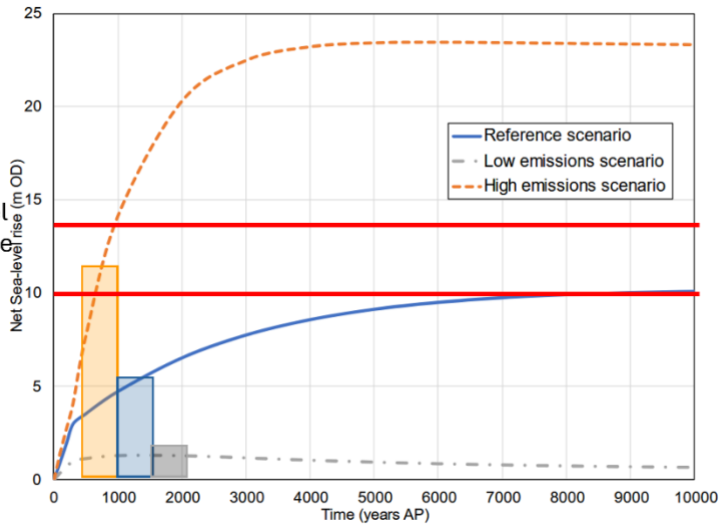

Figure 4.10: Comparison of the time to initial site disruption and the elevation of the cliffs, which informs the mechanism by which site disruption occurs (Figure 4.9)

In the High Emissions Scenario, the mechanism of disruption varies over the projected disruption timeframe (500 to 1,000 years; Table 4.2) as the sea level rises, and in space, owing to the possible different elevations of the vault bases across the LLWR.

- 500 to 600 years: the base elevation of cliffs would be the same as the base of potential future vaults at the south of the disposal area (10 m OD), which would result in direct wave attack and vault erosion. The base of the cliffs would be lower than the base of existing vaults (14 m OD), therefore resulting in site disruption by vault undercutting.
- 600 to around 1,000 years: the base of the cliffs would be at the same elevation or slightly greater than the bases of the vaults (14 m OD). Consequently, the disruption mechanism would be vault erosion by direct wave attack.

In the Low Emissions Scenario, the sea level is projected to be 2 m OD (Figure 3.9) at the time of disruption (1,500 to 2,000 years; Table 4.2). This is below the elevation of all existing and potential future vaults, therefore the disruption mechanism would be by vault undercutting across the site.

In the High Emissions Scenario, periodic coastal inundation by high spring tides and storm tides is projected between around 1,000 and 2,000 years, after which permanent inundation is projected. In the Reference and Low Emissions Scenarios, periodic and permanent inundation would not occur for more than 8,000 years [25].

4.3.7 Estuary Evolution

The Ravenglass Estuary is 2 to 3 km south-east of the LLWR. The evolution of the estuary is an important consideration in understanding the future landscape change.

The morphology of an estuary is controlled by the feedback between the tidal and wave energy, the estuary channel morphology and sediment supply [25]. The tidal prism, which is the total volume of water entering an estuary on the flood tide, controls the tidal energy in the system. The tidal prism is dependent on the size of the estuary channel. As sea level rises, the tidal prism increases and the tidal energy decreases. If sufficient sediment is available to keep up with sea-level rise, deposition occurs on the bed and banks of the channel and the channel dimensions are constant. However, if the sediment supply is insufficient to keep up rising sea level, the channel dimensions increase.

The three rivers (Irt, Mite and Esk) flow into the estuary across a steep hinterland, which limits the tidal intrusion into the estuary and therefore reduces the available tidal power of the system. The evolution and behaviour of the estuary has been largely dominated by this imposed low-power regime and the contrast between it and the high wave energy and sediment movements along the open coast.

The Drigg promontory, which is positioned between the LLWR and the mouth the Ravenglass Estuary, is an important geomorphological feature that will impact the future evolution of the site. It is assumed that the northern part of the spit, which has a core composed of glacial till [54], will be unable to migrate inland, but that the southern part will be mobile. This is expected to limit the movement of the mouth of the Ravenglass Estuary.

4.3.7.1 Approach and Results in the 2011 ESC

In the 2011 ESC, the impact of the estuary evolution on the LLWR was explored using a regime model [51]. The model provided an indication of the estuarine geomorphology at given times in the future, based on sea level and sediment supply scenarios.

The northernmost river, the River Irt, which is located a few hundred metres to the south of the LLWR, is the closest to the site boundary. Morphological changes to this part of the Ravenglass Estuary are considered the most relevant owing to its location and were the focus of the model.

In summary, the model did not identify any scenarios under which estuarine evolution is likely to lead to the disruption of the LLWR within the next few thousand years [34].

- In the scenario where sediment supply is sufficient to keep up with sea-level rise, deposition occurs and the LLWR would be buried.
- In the alternative scenario, where insufficient sediment is available, the tidal channel will increase in size and this could result in a tidal creek re-occupying the former tributary through the LLWR site (the East-West Stream). This could result in erosion; however, the model results suggested that the evolution is highly unlikely to be sufficient to lead to site disruption for the next few thousand years.

4.3.7.2 Updated Approach and Results

As part of the 2026 ESC, the same regime model has been updated with the refined sea-level projections (Subsection 3.6) and updated coastal recession understanding (Subsection 4.2).

Similar to the 2011 ESC, the updated model simulates evolution of the River Irt and its estuary for the purposes of understanding the impact on the LLWR. The updated model represents specific periods, based on the following constraints [25].

- Prior to coastal inundation, i.e. times when sea level does not exceed the present-day coastal hinterland elevation of around 20 m OD.
- When sea level exceeds 10 m OD, the current estuary would cease to exist since the current Irt coastal plain runs into steeply rising land at this level. Sea level rising above this elevation would result in the formation of a subtidal channel because there would be no landward accommodation space for an estuary. This assumption is based on likely future sediment supply, which is thought to be insufficient to allow the extensive coastal plain to accrete vertically in line with sea-level rise.
- Prior to shoreline retreat having not already led to the disruption of the LLWR, or loss of the Irt Estuary following erosion of the Drigg Spit.

Net sea level rises at the times of first site disruption by coastal recession in the Reference and Low Emissions Scenarios are 6 and 2 m OD, respectively (Figure 3.9). These sea levels are lower than the elevations of the LLWR vaults. The tidal prisms at these times would be too small to cause estuary inundation of the LLWR site.

In the High Emissions Scenario, net sea-level rise is projected to be 10 m OD at the time of initial site disruption by coastal recession (Figure 3.9). The southern part of the LLWR, future vaults may be constructed with a base elevation of 10 m OD or more. In the High Emissions Scenario, the tidal prism would be large enough to inundate the relatively low-lying southern areas of the site. If sediment supply is low, the estuary could erode these areas; however, this is considered unlikely as the receding cliffs will be supplying a high volume of fine-grained sediment and there is expected to be an absence of high-energy waves in this area, owing to its relatively sheltered location [25].

Hypothetically, high sediment supply from the receding coast could cause deposition within and blockage of the mouth of the Ravenglass Estuary, leading to potential freshwater flooding of the coastal plain. This hypothetical evolution is also considered unlikely because the tidal prism would be large enough to maintain the estuary mouth [25]. The consequences of such flooding are considered in the assessment of impacts during the PoA [13].

In summary, the results of the updated model show that the future estuary size is smaller compared with the 2011 ESC model, because the projected sea-level rise is lower. As a result of its smaller size, it remains unlikely that the LLWR would be disrupted by estuary processes irrespective of sea level and sediment supply.

4.3.8 Site Erosion

After the repository is first disrupted, its continued erosion will be controlled by the same processes as those that controlled the hinterland erosion. As the site erodes, different sized

particles of waste and engineered materials will be sorted and transported in the coastal system as follows:

- fine-grained and/or low-density particles will be transported offshore;
- sand-sized particles or those of equivalent density will be stored on the intertidal beach (foreshore) and freely transported along the entire coastal cell;
- gravel-sized particles will form a storm beach; and
- larger/denser materials will tend to be immobile.

A key control on erosion rate is the size of the storm beach; the larger the storm beach, the greater protection it provides to the cliffs and lower the rate of erosion. The size of the storm beach will depend on the amount of gravel-sized material supplied from eroding repository. The strength of the gravel-sized materials released from the eroding repository will control its residence time on the storm beach and its protective effect through time.

The size and strength of the gravel-sized material supplied to the beach are controlled by the original make-up of the engineered and waste materials when first emplaced. They will also be controlled by the condition of the engineered and waste materials when they are eroded, recognising the properties of some vault and waste materials are likely to change over time, with concrete and grout progressively degrading and metals corroding.

4.3.8.1 Conceptual Understanding

The condition of the waste and engineered materials when the LLWR is disrupted by erosion is described in the *'Near Field'* report [6].This is combined with observations of eroding coastal sites to provide a conceptual understanding of the erosion of the LLWR, including the in-situ degradation of wastes and engineered materials, their transfer to the beach and dispersal in the coastal system [25].

Figure 4.11 shows a schematic view of the LLWR, including the vaults, trenches and cap. The vault walls and bases are constructed from reinforced concrete. The vaults contain or will contain mostly mild steel ISO containers, as well as potentially a limited number of mild steel Standard Waste Transport Container (SWTC)-compatible strong boxes. It is expected some waste in the UKRWI could be packaged in 'durable' containers. Durable containers are those composed of stainless steel, thick-walled concrete or cast iron that are expected to be significantly more resistant to degradation than ISO containers. However, our position is to exclude the bulk disposal of these durable containers. This is because of the potential impact of a substantial number of durable containers on the eroding repository and the resulting consequences for the radiological impact assessments and amenity value of the beach. However, this does not preclude disposal of small quantities of durable containers in the surface vaults on a case-by-case basis and subject to bespoke assessment. Some durable containers have already been disposed to Vault 8, and these are taken into account in the following projections.

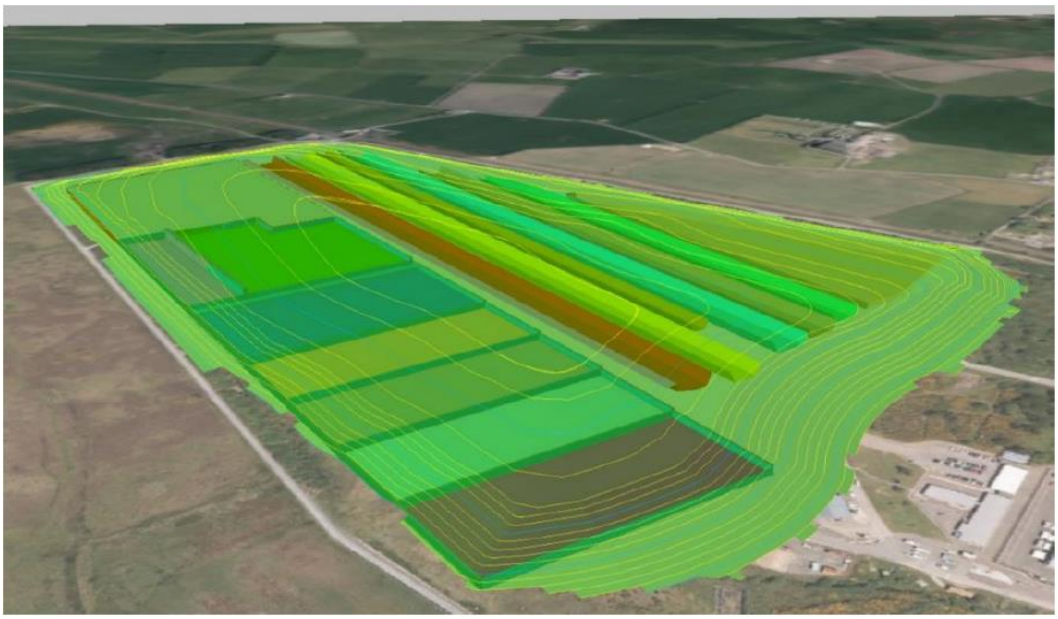

Figure 4.11: Layout of the LLWR, showing the vaults (Vault 8 in the background moving to Vault 14 in the foreground) and trenches overlain by a cap (in green). The cap comprises multiple layers, including gravels [5].

Shielded modules would be built for ILW containers that require operational shielding. These structures are expected to be composed of thick (approximately 600 to 750 mm) reinforced concrete [25].

The trenches contain a range of different waste types, including cellulosic wastes, rubbers, metals, plastics, glassware, ceramics, bricks and concrete. The cap will comprise multiple engineered layers, such as soils, geotextiles, gravels and sands [63].

In-situ degradation prior to site disruption

At the time of initial site disruption, the degradation of the vault concrete is expected to be limited [25].

- Non-throughgoing cracks may form in the concrete after a few hundred years following emplacement, as a result of expansive corrosion of the rebar.
- Consistent with the specification, cracks will form in the concrete in the vault bases because of operational loading. These cracks would be weak points; however they would not lead to breakages, owing to the rebar, which would be continuous across the cracks. The rebar crossing these cracks may be subjected to elevated corrosion and therefore further cracking and weakening of the concrete.
- Surface leaching of structural concrete components exposed to the rain is expected during the operational phase.
- Carbonation could occur on the surface of all structural concrete components because of reactions with atmospheric CO_2 during the operational phase. It could also occur

following closure as a result of CO_2 generated by microbial degradation of organic waste; however, post-closure degradation is considered unlikely as the pH in the grouted wastes is likely to limit microbial activity.

During the operational phase, waste containers will be subjected to corrosion in the atmospheric conditions prior to cap emplacement. Once the cap has been emplaced, the vaults are expected to be humid enough for the corrosion of the containers [25]. Taking into consideration the expected pH conditions in the vaults and corrosion rates, as well as the associated uncertainties, the timescales to completely corrode the container walls are expected to be longer than the longest timeframe for erosion of the hinterland (i.e. based on extrapolation of historical rates for conditions of little or no relative sea-level rise). Therefore, the containers will be degraded but largely intact when the LLWR is first breached by coastal erosion.[6]

The trench wastes are expected to be significantly degraded when the trenches start to be disrupted by coastal erosion. The degraded trench wastes are expected to comprise silt-sized material (residues of degraded organics, rubbers and plastics, and metal corrosion products), inorganic soil materials, partially degraded lumps of concrete, broken but undegraded glass, bricks and ceramics, and potentially some partially degraded resilient metals and plastics.

In-situ degradation after site disruption

The repository vaults will be subjected to undercutting or direct wave attack at the time of first site disruption, depending on the climate projections (Subsection 4.3.6).

The vault bases are not designed to act as cantilevers. In the undercutting scenario, once the vault bases have been undercut by a critical distance, they will break, causing the base slab and any overlying walls, containers, capping materials to collapse onto the storm beach. In the direct wave attack scenario, storm waves will penetrate the vaults at high tide, leading to collapse or slumping of repository materials onto the storm beach. In both scenarios, the waste containers and engineered components in the cliffs will be exposed to atmospheric oxygen, sea spray and potentially also waves (water, chloride and sulphate in addition to physical impact). This will result in sulphate attack of concrete and elevated metal corrosion rates. These processes will impact the properties of the engineered materials and wastes and influence the evolution of coastal system.

Sulphate attack of concrete exposed in the cliffs, and immediately behind it, will result in cracking and weakening of the concrete. It will reduce the isolation of the rebar in the concrete, exposing it to oxic and saline conditions. Therefore, the rebar will corrode more quickly, which will cause further cracking and weakening of the concrete. Sulphate attack is expected to be greater during direct wave attack because the concrete would be exposed to more regular wave

6 Surcharging of containers in Vault 8 (discussed in the 'Engineering' report) will mean that these containers will be mildly structurally compromised, leading to a slight acceleration of dispersal, but this is not considered to be a significant difference.

splash. It will also be greater when the concrete is exposed in the cliff for longer (i.e. when erosion rates are low), as there will be more time for attack.

The vault walls are not formed from sulphate resistant concrete. They will likely be intact at the time when they collapse out of the cliffs when erosion rates are high (i.e. High Emissions Scenario) because of the relatively limited time for sulphate attack. At lower rates of erosion (i.e. Reference and Low Emissions Scenarios), the vault walls may be exposed in the cliffs for several decades, so they may be starting to break up when they collapse out of the cliffs. The extent of sulphate attack in the vault walls will also depend on the orientation of the walls relative to the erosion front. The east and west vault walls would be crudely parallel to the erosion front. As a result, relatively large areas of the walls may be exposed in the cliff and subjected to sulphate attack. Conversely, a relatively small area of the north and south walls would be exposed.

In addition to concrete degradation, waste containers exposed in the cliffs will corrode. Corrosion rates of mild steel waste containers exposed in the eroding cliffs, which are estimated using analogue information and expert elicitation, are compared with erosion rates to understand the condition of the waste containers, at the time when they collapse onto the storm beach [25].

Assuming oxic and saline conditions extend a few metres into the exposed repository in the cliffs, the ISO containers are expected to have substantially to fully corroded in situ, prior to their collapse onto the storm beach at low erosion rates (i.e. in the Low and Reference Emissions Scenarios). When they collapse onto the storm beach, the remaining container would break up and disgorge its contents. At higher erosion rates (i.e. in the High Emissions Scenario), when the ISO containers collapse out of the cliffs onto the storm beach their walls may only be partially corroded and their structural elements may not be significantly reduced. Some containers may remain intact on the storm beach for years to several decades [25].

Beach characteristics

At the time of initial site disruption, the characteristics of the beach adjacent to the LLWR will vary depending on the erosion rates, because of their control on the degradation of the waste and engineered materials.

When erosion rates are high (i.e. in the High Emissions Scenario), large pieces of concrete and intact to partially collapsed ISO containers are expected to be positioned at the toe of the cliff (Figure 4.12). In general, the number, size and range of man-made materials would decrease with increasing distance from the cliffs across the storm beach and onto the foreshore. The ISO containers would be present on the storm beach, becoming increasingly degraded and broken up with increasing distance from the cliffs. Large pieces of concrete, pieces of grout and waste items would be present on the coastal side of the storm beach and could be present on the upper parts of the foreshore.

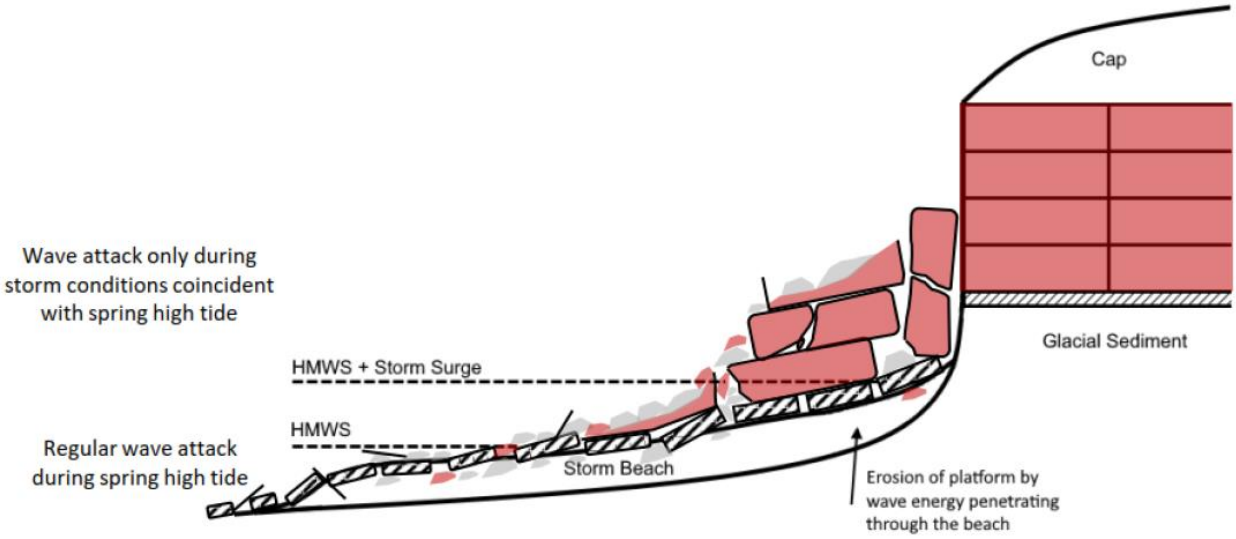

Figure 4.12: Schematic section through the eroding cliffs and storm beach showing the distribution of engineered and waste materials

At lower erosion rates (i.e. the Reference and Low Emissions Scenarios), the beach is expected to contain fewer containers, resilient waste items and large pieces of concrete because these engineered and waste materials would have been in situ in the exposed cliffs for longer and therefore will have degraded to a greater extent prior to collapse.

Large engineered and waste materials on the storm beach are expected to absorb some wave energy, possibly slowing the erosion of the repository in the adjacent cliffs. However, in this scenario, the engineered and waste materials in exposed cliff will be subjected to greater in-situ degradation. They will be weaker once they have collapsed onto the storm beach and therefore will provide less protection in the future. Furthermore, storm waves would be expected to funnel between the large engineered and waste materials at the toe of the cliffs. These waves would penetrate the repository, promoting erosion and degradation. Godwin Battery at Kilnsea on the Holderness coast and Walney Island landfill in South Cumbria are analogues that demonstrate wave funnelling [25]. At these locations, storm waves penetrate between man-made materials on the storm beach, limiting their protective effect.

The protection provided by the large engineered and waste materials may result in a subtle curvature of the coast (i.e. development of a small headland; Figure 4.13). The projected morphology is similar to the current coastal morphology at Barn Scar, where cobble and boulder deposits provide greater protection against erosion, compared with the adjacent coast [25].

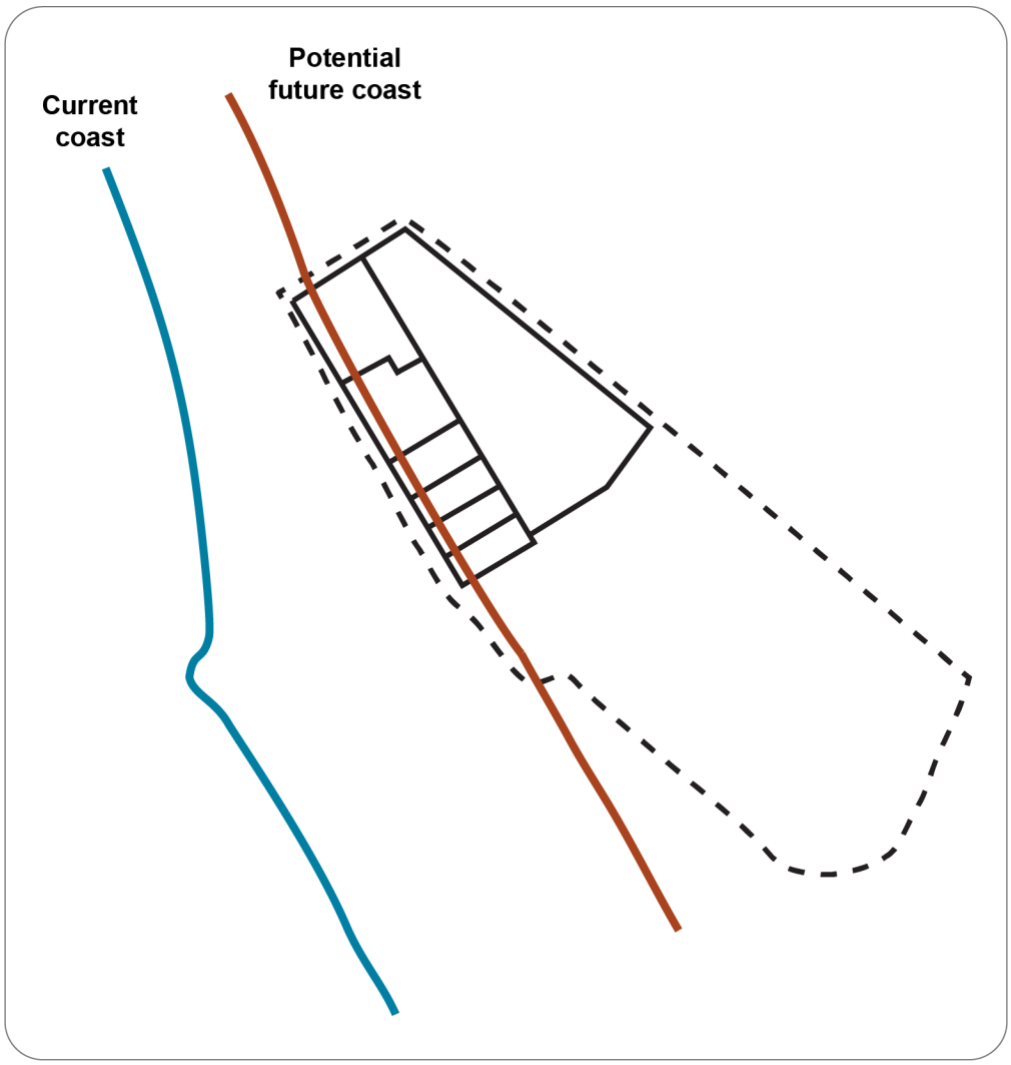

Figure 4.13: Potential subtle curvature of the future coastline due to short-lived coastal protection provided by large engineered and waste materials as the vaults start to be eroded [25]

Break-up and dispersal of repository materials

We have used further analogues of eroding coastal systems comprising man-made materials to understand the break-up and dispersal of the LLWR engineered and waste materials once they fall onto the beach [25].

Intact and partially degraded ISO containers positioned at the toe of the cliff will be subjected to corrosion and, to a lesser extent, storm wave impact. These processes will weaken the containers and cause failure. The walls of the containers are thinner than the structural elements. Therefore, the walls will fail first, causing the waste and grout to disgorge under their weight or from storm wave impacts.

The broken metals from the failed containers (e.g. the container walls and structural elements) will remain on the storm beach because they will be large and heavy. They will continue to

degrade by corrosion and wind and wave abrasion, with some small pieces possibly being rolled and abraded by storm waves.

The grout from the waste containers will fall onto the storm beach once the containers fail. It will be subjected to sulphate attack, which will cause cracking and reduce its resistance to physical degradation. It will be broken up by wave impact and waterborne attrition. As the sea level rises and erosion proceeds, grout blocks will become stranded further away from the cliffs on the storm beach. It will ultimately break down to fine-grained material and be transported offshore.

Some wastes will be fully or significantly degraded when they are disgorged from the failed containers. Other wastes, such as resilient metal items, glassware, ceramics, bricks and concrete, will be intact. The wastes will be subjected to degradation processes on the storm beach, including wave impact, attrition, abrasion and corrosion. As these processes proceed, fine-grained material will be generated and transported offshore, and cobble and gravel-sized materials will remain within the storm beach as it migrates landward. Larger boulder-sized materials be immobile and therefore be stranded progressively seaward as coastal erosion continues.

Durable containers will resist degradation processes to a greater degree than ISO containers and could remain on the foreshore up to for hundreds of years [25]. A single large vault of durable containers collapsed onto the storm beach would protect the adjacent coast, leading to locally lower erosion rates and the possible formation a headland. Any durable containers that are disposed of in the LLWR would not be disposed of in such configurations. They will be disposed of in small groups with optimal spacings to ensure that when they collapse onto the storm beach they form small piles rather than coalescing into one large pile. The small piles would limit the protective effect of the durable containers because storm waves would be able to funnel between them [25].

Reinforced concrete will be subjected to continued expansive corrosion of the rebar and sulphate attack on the storm beach. Both processes will weaken and crack the concrete, resulting in the generation of cobbles and gravel-grade concrete. Attrition will also be active, wearing down the cobbles and gravels to fine-grained concrete, which will be transported offshore. Larger pieces of concrete will become stranded down the storm beach and possibly foreshore as erosion proceeds, before eventually wearing down to fine-grained materials and being transported offshore. The shielded modules are expected to be composed of thick and therefore relatively resistant concrete. The collapsed modules will be immobile and will likely persist across the storm beach and onto the foreshore. On the storm beach, they could form a small rocky headland at and around the high tide mark. On the foreshore they could be cut-off by the tide, promoting the accumulation of sediments and formation of a spit [25].

Wastes from the trenches (e.g. organics, rubbers, plastics, metals, soils, concretes, ceramics, bricks and glasses) are expected to be significantly degraded by the time they fall onto the beach. Plastics are expected to be rapidly moved onshore or offshore by wind action or be eroded and weathered to micro-plastics. Other wastes will be subjected the same degradation

processes as the vault wastes, including wave impact, attrition, abrasion and corrosion, ultimately breaking down to fine-grained materials and being transported offshore.

4.3.8.2 Site Erosion Modelling

The CRM and SCAPE models used to estimate the time to initial site disruption (Subsection 4.3.4) are also used to simulate the complete erosion of the LLWR.

Coastal recession modelling

CRM is used to explore the timescale of compete loss of the repository. Given the timescales to site erosion and potential compounding of error, the model is restarted at the point the site is first exposed to erosion (i.e. the western walls of the vaults). As described previously, this time varies from 750 to 1,750 years, depending on the sea-level projections (Table 4.2).

The sea level at these times in each scenario (Figure 3.9) is a key input parameter to the CRM. Other key input parameters are those that describe the sediment budget, including the initial beach volume and the amounts of gravel supplied to and lost from the storm beach. These parameters represent the protective effect of the storm beach and its impact on the rate of coastal erosion.

The beach volume at the start of each model run is set at 80 m^3 m^{-1}, based on the results of the CRM modelling of the hinterland erosion and aligning with current beach volume [25].

The amount of gravel supplied to the storm beach from the eroding repository in the cliffs is dictated by the degree of in-situ degradation of the engineered and waste materials. Two gravel scenarios are used in the CRM to capture end member degradation states of the engineered and waste materials.

- In the low gravel scenario, it is assumed that concrete and grout have degraded to silt and half of the waste materials are fine-grained and half are gravel. The gravel supply is limited to concrete aggregates, waste soils and coarse cap sediments.
- In the high gravel scenario, a low degree of degradation of concrete and grout is assumed, with gravels comprising 80% of the waste materials [25].

The amount of gravel lost from the storm beach is represented by the clast attrition rate. This is assumed to be 2% of the beach volume loss per year. This rate is higher than the rate used for glacial sediments in the hinterland erosion modelling, reflecting the relative softness of concrete and bricks and their likely short-lived persistence on the storm beach. It is based on observations from the analogue Walney Island landfill, where bricks and concrete rubble degrade from angular in the cliffs to rounded on the beach over a few decades [25].

For each of the three sea-level projection and two gravel scenarios, the CRM is run from the vault wall on the seaward side of the repository to the site boundary adjacent to the railway. It is run along two profiles (Carl Crag Line C and D) that transect Vaults 8 and 10 and equate to 325 m and 500 m erosion, respectively. Modelling further to the south (i.e. south of the disposal

area) was not undertaken because the profile is considered too long to confidently simulate its erosion [25].

SCAPE modelling

Initial site disruption is projected to be by vault undercutting in the Reference and Low Emissions Scenarios and by vault undercutting and vault erosion in the High Emissions Scenario, depending on the location along the LLWR western boundary (Subsection 4.3.6).

The geological model of the site indicates the glacial sediments beneath the repository are varied but not significantly different to those of the present coast [25]. Although variability in the glacial sediments is recorded (Subsection 4.3.2), the bulk make-up of the sediments in the base of the eroding cliffs when the undercutting mechanism is disrupting the repository is assumed to be similar to the bulk make-up (and strength) of the glacial sediments that have been eroded from the hinterland. The engineered and waste materials from the repository will not be eroding, instead they will collapse onto the beach, because of the undercutting. The SCAPE model used to simulate the hinterland erosion in the Reference and Low Emissions Scenarios is considered appropriate to simulate the erosion of the repository, owing to the bulk similarity in the eroding sediments [25].

Although consistent with the geological model, this assumption does not take account of the natural variability in the strength of the eroding sediments. Multiple runs of the SCAPE model have been undertaken varying the material strength parameter by ±50% to represent its natural variability. The variation in the strength parameter also represents the changes in material properties associated with direct erosion of the repository notably in the High Emissions Scenario.

4.3.8.3 Site Erosion Projections

The estimates for the time to completely erode the repository based on the CRM and SCAPE model are presented in Table 4.3. As previously discussed, the CRM results are interpreted to be overestimates of erosion timescales (underestimates of the erosion rate) because of uncertainties in the underpinning empirical datasets and compounding of errors when the model is run for very long timescales. The SCAPE results are considered to be underestimates of the erosion timescales (overestimates of the erosion rates).

Considering the uncertainties in the models, the timescales for complete erosion of the repository are expected to be in between the CRM and SCAPE model results. They are (Table 4.3):

- 2,000 to 3,500 years for the Reference Emissions Scenario;
- 1,500 to 3,000 years for the High Emissions Scenario; and
- 2,500 to 4,000 years for the Low Emissions Scenario.

These estimates do not reflect the specific profiles (i.e. those used in the initial site disruption projections; Figure 4.5 and Table 4.2). It is expected that the coastal geometry will have changed by the time of site erosion and, given the uncertainties, it is not considered appropriate to distinguish between the profiles for the complete site erosion estimates.

Table 4.3: Summary of the time to complete repository erosion, based on coastal recession projections [25].

Projection approach	Years for complete site erosion (after initial site disruption)		
	Reference Emissions Scenario	**High Emissions Scenario**	**Low Emissions Scenario**
CRM (Carl Crag C)	1,600	>1,150[a]	1,600
CRM (Carl Crag D)	>2,500	>1,150[a]	>2,500
SCAPE model (Carl Crag)	700 to 900	300	>900
Expert judgement range	1,000 to 2,000	1,000 to 2,000	1,000 to 2,000
	Years for complete site erosion (after present)		
Expert judgement range	2,000 to 3,500	1,500 to 3,000	2,500 to 4,000

[a] In the CRM, the High Emissions Scenario results reflect a lower end of the range. The mean sea level reaches the hinterland elevation (20 m OD) before the repository has been completely eroded (at 1,150 years after initial site disruption). The repository will be inundated at this time.

The mechanisms by which the repository erodes (i.e. undercutting, wave attack and inundation; Figure 4.9) are expected to change as the erosion proceeds. This results from the rising sea level, and therefore the erosion mechanisms vary according to the climate scenarios.

In the Reference Emissions Scenario, erosion is by mostly undercutting and direct wave attack [25].

- For times beyond the upper estimate of the repository erosion (>3,500 years; Table 4.3), the base of the existing vaults and trenches (14 m OD) remains above the base of the cliffs. As a result, erosion in this area of the repository will be by vault undercutting.
- After approximately 1,200 years AP, the base of the cliffs will be above the base elevation of the proposed future vaults (10 m OD), meaning this area of the repository will be eroded by direct wave attack.

- Towards the upper end of the range of timeframes for erosion of the repository (e.g. up to 3,500 years AP), the base of the future vaults are expected to be approximately 4 m below the base of the cliffs. These vaults may be exposed below the storm/upper beach or on the upper part of the intertidal shore platform, where they will experience periodic inundation and wave action.

After approximately 600 years AP in the High Emissions Scenario, the base of the existing and future vaults, as well as the trenches (10 to 14 m OD), will be below the base of the cliff. Therefore, all vaults will be subjected to direct wave attack. By 2,000 years AP, which is within the range of estimates for complete repository erosion (1,500 to 3000 years; Table 4.3), the relative sea level will exceed the hinterland elevation and the hinterland will be inundated. Prior to and during early inundation, the wastes in the eastern areas of the repository would be periodically exposed on the foreshore between mobile sand bars, similar to peats that are periodically exposed on the current foreshore (Figure 4.14) [25]. The wastes would be subjected to erosion by wave action. In a storm, exposed waste will be scoured out to a shallow depth by swash waves and any resulting shallow hollow will be backfilled with a mixture of waste and sand by the subsequent backwash. The wastes are expected to become protected by an upper layer comprising a mixture of waste and beach material. As a result, residence times for wastes exposed on the foreshore may be hundreds of years or more [25].

Figure 4.14: Peat periodically exposed in a shallow depression on the Drigg foreshore. This is analogous for waste exposure under a High Emissions Scenario sea-level projection [25]

In the Low Emissions Scenario, the complete erosion of the repository will be undercutting because the elevation of the base of the future cliff is below the elevation of the base of the existing and future vaults, as well as the trenches (10 to 14 m OD), beyond the 4,000 years after the upper estimate for complete erosion [25].

Summary of Site Erosion

Reference Emissions Scenario

Cliff Composition: Initially a basal layer of glacial sediment overlain by waste material, proceeding to a cliff comprising of waste material only.

Beach Composition: A mix of sand and gravel from both glacial sediments and eroded repository materials (e.g. cap and profile layers, concrete, waste containers).

Erosion Dynamics: Vaults are undercut as sea level rises to just below their base. Collapse of vaults leads to waste tumbling onto the beach, where it is reworked by waves.

Low Emissions Scenario

Cliff Composition: Similar to the Reference Emissions Scenario – glacial sediment at the base, waste above.

Beach Composition: Lower supply of beach-building material due to slower erosion and more degraded waste.

Erosion Dynamics: Slower cliff recession allows more time for in-situ corrosion of rebar and concrete cracking. Undercutting leads to smaller concrete fragments on the beach. Reduced sediment supply may cause beach lowering and increased undercutting.

High Emissions Scenario

Cliff Composition: Likely to be composed entirely of waste materials.

Beach Composition: Higher proportion of sand and gravel from the repository, including cap and profile materials that are at least 5 m thick

Erosion Dynamics: Direct wave attack from the outset. Greater potential for preservation of deep vault and trench waste on the shore platform. 'Extended talus' of waste and engineered material forms at the cliff base

4.3.9 Consideration of Coastal Defences

Coastal defences, if maintained, could be an effective way to prevent erosion over tens to a few hundreds of years. On the West Cumbrian coast, defences and railway embankments are present and have reduced sediment supply since the 1840s [51]. However, rising sea levels are expected to minimise the effectiveness of the coastal defences in preventing coastal erosion. Analogues provide insights into the effectiveness of coastal defences [25]:

- Godwin Battery was constructed on the Holderness coast between 1914 and 1915, as part of the outer Humber wartime defences. It was protected by a 300-yard-long sea wall

with a concrete blockhouse in the centre, and wooden groynes on the foreshore. However, at some time between 1960 and 1969, the sea wall, which had not been maintained, failed.

- Walney Island landfill in South Cumbria was operational until the 1980s. In around 2010, the landfill was exposed to coastal processes as a result of cliff recession. A limestone armour was constructed to limit erosion, however, this was breached by a storm event in 2018.

In both of these analogues, waves have been able to penetrate between the breached defences allowing coastal erosion to continue. Sea-level rise will make defences even less effective. Therefore, it is not considered feasible for us to guarantee protection from erosion over many hundreds to a thousand years using engineered structures, and we cautiously assume no coastal defences will be present in the projected estimates.

This position is consistent with regulatory guidance, which requires the repository to be passively safe without ongoing management and maintenance. Any future generation that chooses to implement and maintain coastal defences would do so with knowledge of the hazard presented by the facility and would thus implement controls to ensure it is safe.

4.3.10 Summary of Progress Since the 2011 ESC

The 2026 and 2011 ESCs use the same conceptual model to describe coastal evolution, the same multi-evidence approach to projecting change, and similar assessment tools to assess cliff recession rates and patterns of estuary evolution. The resulting timescales to repository impact are different, principally due to changes to the sea-level projections, which are for lower magnitudes and lower rates of rise, but also due to refinements in the assessment tools and their parameterisation.

The coastal evolution conceptual model has been systematically reviewed using data from an annual coastal inspection programme carried out over the past ten years, along with findings from other studies of the West Cumbrian coast, including those commissioned for Sellafield.

Projections for the 2026 ESC are based on three carbon emissions scenarios with a clear, logical link between carbon emissions, climate change, sea-level rise and rates of coastal erosion. The nature of underpinning climate projections at the time of the 2011 ESC meant that such an approach was not possible.

Two different numerical modelling approaches were used to model cliff recession and hinterland erosion in support of the 2011 ESC (CRM and SCAPE modelling) [34]. The two approaches help to provide erosion timescales within appropriate ranges, rather than providing specific predictions.

The CRM and SCAPE model considered the low and high sea-level scenarios that were used to underpin the 2011 ESC. The model results were compared to critical recession distances, which are the distances to the LLWR site boundary from the coast at different representative positions

along the coast. This comparison provided estimates of the time at which the LLWR would be first disrupted by cliff recession, which were several hundred to approximately 1,000 years AP [34].

In 2017, we undertook a review of erosion modelling approaches and developments in coastal science and concluded that that CRM and SCAPE continue to be effective tools for modelling the west Cumbrian coast [45].

The 2026 ESC adopts the same modelling philosophy as 2011 ESC, which is to use multiple complimentary approaches that provide projections within appropriate ranges, rather than providing specific predictions. It builds on the large body work that underpinned the previous ESC to assess the timescale for erosion by implementing refined coastal recession and SCAPE models, as well as two simpler methods; the Bruun rule and the extrapolation of historical cliff recession rates. The extrapolation of historical rates offers greater value in this report than was the case in 2011, because the projected sea-level rise under the Low Emissions Scenario more closely aligns with historical trends. Additionally, data from our coastal inspection programme have validated the anticipated rate of erosion under these conditions.

The refined approaches reflect improved sea-level rise understanding that is based on internationally recognised emissions scenarios. Furthermore, the CRM also accounts for recent coastal monitoring data, and therefore better represents the sediment budget of the coastal system. Collectively, the refined approaches indicate that the initial disruption of the site could occur later than suggested in the 2011 ESC.

Based on the understanding of the sea level at the time of disruption, the main mechanism leading to repository disruption is vault undercutting. However, direct wave attack on exposed engineered structures is possible under the Reference and High Emissions Scenarios, and parts of the repository may be inundated in the High Emissions Scenario. The assessments in the 2011 ESC similarly suggested vault undercutting would be the main disruption mechanism.

This current study has built on the information provided for the 2011 ESC and subsequent studies by describing the fate of the waste once it has eroded from the repository and entered the coastal system, and considering the potential impact of large numbers of ISO containers, large pieces of repository engineering and large waste items on coastal processes through observations of analogous sites.

5 Summary

Overall Outcomes

A fundamental component of the ESC for any radioactive waste disposal facility is a demonstration of an understanding of the future evolution of the site, its environmental setting, and related uncertainties, all based on sound science. This provides important input to estimating the future performance of the facility and the site. This document presents the understanding of processes that are important to site evolution and summarises the underpinning evidence base.

Projections of global climate change are based upon the latest predictions of global climate change. Projections for ranges of future sea-level rise for the West Cumbrian coast in the vicinity of the LLWR are provided, together with an overview of remaining uncertainties. These ranges in turn inform projection of potential future coastal change near the LLWR.

This document summarises the outcomes of a significant programme of work that has been ongoing for several decades to:

- identify projections of the potential evolution of the global climate and thus the likely evolution of sea level in the vicinity of the LLWR;
- develop a robust understanding of the characteristics, processes and thus potential evolution of the coastal system in the vicinity of the LLWR;
- integrate that understanding to present projections for future site evolution and coastal evolution suitable to underpin the ESC.

This programme has included a systematic analysis of developments in understanding of potential global climate change from international bodies and programmes such as the IPCC and UK Met Office. The information has been further interpreted to understand potential impacts in the vicinity of the LLWR. Knowledge in this area has improved greatly since 2011, although uncertainties remain (in particular, relating to future emissions of CO_2, ice-sheet stability and global sea-level rise).

Coastal processes at the LLWR are well characterised through analysis of historical maps and photographs, contemporary observations, interpretation and predictive modelling. Uncertainties have been identified and characterised as far as possible and are represented in the key outcomes (e.g. timescales of disruption) using ranges.

Overall, the outcomes of the analyses presented in this document are robust and provide important supporting information to underpin high-level arguments made elsewhere in the ESC. They also support key aspects of the conceptual models underpinning assessment calculations reported elsewhere.

GRA Requirements

The report addresses a range of aspects of the GRA, and in particular Requirement R11 (Site Investigation). Areas covered include the following:

- 7.2.1(a): The environmental safety case should demonstrate a clear understanding of the disposal facility in its geological setting ('the disposal system') as it evolves.
- 7.3.29: As far as possible, use standard approaches to establish the environmental safety case, thus relying on appropriate expert judgement in gathering and interpreting evidence and applying it to construct and use the qualitative and quantitative models.
- 7.3.32: Take into account the potential for climate change.

The content of the report also supports other aspects of the ESC, such as the radiological impact assessments [14], which in turn address other aspects of the GRA.

We have employed appropriate approaches to develop the understanding and projections made, from the perspective of coastal and landscape evolution. A wide range of evidence sources have been used for coastal characterisation and appropriate modelling approaches. Appropriate cognisance is taken of international understanding and expert judgement on climate change, and the projections made were supported by detailed expert review meetings on key aspects of understanding.

Climate and Sea-level Projections

Three emissions scenarios – Reference, Low, and High – are used to capture the range of possible future greenhouse gas pathways. Climate projections and sea-level rise at the LLWR site are based on downscaled global models and local meteorological data.

- Reference Emissions Scenario: CO_2 emissions remain at current levels until mid-century before declining.[7]
- Low Emissions Scenario: CO_2 emissions decline rapidly, reaching net zero after 2050, followed by net negative emissions.
- High Emissions Scenario: CO_2 emissions roughly double by 2050, peaking around 2090, with high atmospheric concentrations persisting.

Projected Temperature and Precipitation Changes

Under the Reference Emissions Scenario, mean annual temperature at the LLWR site is projected to peak at +2.4 °C above 1981 to 2010 values around 300 years AP, returning to +0.5 °C by 10,000 years AP. In the Low Emissions Scenario, peak warming is limited to +1 °C at 100

[7] For the PoA we adopt the High Emissions Scenario as the central case in our assessments, reflecting regulatory advice

years AP before declining to +0.1 °C by 10,000 years AP. For the High Emissions Scenario, warming is most pronounced, with temperatures reaching a maximum of +7.4 °C at 300 years AP and remaining elevated at +2.6 °C at 10,000 years AP.

The climate maintains a general classification of 'temperate oceanic' under both the Reference and Low Emissions Scenarios, reflecting a biosphere similar to that of the present day. Under the High Emissions Scenario, the climate transitions to a 'humid subtropical' classification for a period, similar to present-day Portugal. Higher emissions scenarios project more intense warming and wetter winters, with drier summers.

The projected climate changes have been considered as part of the EPA [12] in determining cap infiltration and resilience. Whilst climate change may lead to a change in vegetation characteristics, sufficient moisture will always be available in the cap to sustain vegetation and thus resist erosion. The uncertainties in the performance of the hydraulic barriers are more significant than uncertainties in HER.

Sea-level Rise Projections

Relative sea-level rise, accounting for changes in both water and land level at the LLWR site is projected to reach 10 m (Reference), 23.3 m (High), or 0.7 m (Low) above present by 10,000 years AP.

These projections are derived from models that integrate both global and local factors influencing sea level. Global eustatic changes, such as thermal expansion of ocean water due to increased temperatures and the melting of polar ice sheets, are combined with small but ongoing local isostatic adjustments.

Coastal Evolution and Site Disruption

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

Several complementary modelling approaches have been deployed to forecast the rates and mechanisms of coastal erosion and to estimate the timing of repository site disruption at the LLWR facility. These approaches include the use of both empirical and process-based tools such as the Coastal Recession Model (CRM) and the Soft Cliff and Platform Erosion (SCAPE) model, which are further supported by monitoring and analysis of historical shoreline movement, a detailed understanding of the coastal conceptual model and extrapolation of historical erosion rates.

It is not considered feasible to guarantee protection from erosion over many hundreds to a thousand years using engineered structures. We make no provision for coastal defences and cautiously assume no future organisation would construct them. This position is consistent with regulatory guidance, which requires the repository to be passively safe without ongoing management and maintenance.

The principal processes leading to repository disruption are anticipated to include progressive undercutting of coastal cliffs, direct wave attack on exposed engineered structures, and particularly under the High Emissions Scenario, episodic or sustained inundation due to rising sea levels. These mechanisms, acting in combination with ongoing coastal retreat, will ultimately result in the gradual exposure, fragmentation, and dispersal of repository materials into the adjacent coastal environment.

Waste and Engineered Material Behaviour

At the time of disruption, waste containers and engineered barriers may have undergone partial degradation, affecting their resistance to further erosion and dispersal.

The beach composition adjacent to the eroding repository will include sand, gravel, concrete fragments, and potentially resilient waste items, depending on the scenario and rate of erosion.

Analogues and monitoring have informed our understanding of how engineered and waste materials will fragment and disperse in the coastal system.

At the time of initial disruption, waste containers and engineered barriers within the repository may have already experienced varying degrees of physical and chemical degradation due to long-term exposure to environmental processes. This degradation could diminish their structural integrity, influencing both their ability to resist further coastal erosion and the likelihood of waste material release and dispersal.

As the coastline recedes and erosion reaches the vaults, the adjacent beach environment will evolve as well. It is expected to consist of a mixed assemblage of natural and waste materials, including sand, gravel, eroded concrete fragments from the repository structures, and possibly residual waste items that prove more resistant to weathering and transport. These materials will interact with tidal and storm-driven processes, affecting their distribution along the coastal zone and potentially further afield.

Our understanding of how engineered barriers and wasteforms fragment, degrade, and move within a dynamic coastal system has been informed observations from analogous sites where similar materials have been released into coastal environments.

Uncertainties and Management

The projections carry significant uncertainty due to:

- Future greenhouse gas emissions, global and regional climate responses, and ice-sheet behaviour.
- Complex interactions between coastal geomorphology, sediment supply, and storm impacts.
- Long-term modelling limitations and the extrapolation of historic rates to future, unprecedented conditions.

Therefore, the outcomes of the projections need to be treated with caution. While the analyses confirm that it is highly likely that the LLWR will be disrupted by coastal erosion at some point post closure, the timescales are best expressed within broad ranges. We continue to reduce relevant uncertainties through ongoing coastal monitoring, which will become more valuable as climate change and site evolution become more apparent in the coming decades. We have also included several research and development activities related to this area in the ESC forward plan.

A summary of key uncertainties, their management, and our proposals for reducing them are provided in Table 5.1. These uncertainties are managed throughout the ESC, such as in the *'Assessment of Long-term Radiological Impacts*' report [14].

Table 5.1: Summary of key uncertainties and their management within this report.

Description of uncertainty	Impact of uncertainty	Management of uncertainty
Rate and magnitude of future sea-level rise: Estimates for future sea-level rise depend fundamentally on climate projections, for which there are significant uncertainties. The largest are those associated with political and economic factors, which affect greenhouse gas emissions. There are also significant scientific uncertainties surrounding the effect of global climate change on sea level, such as the responses of large ice sheets to temperature rises, and the associated feedbacks for ocean circulation and climate.	The rate of sea-level rise is a principal parameter used in CRM and SCAPE modelling, and adoption of different sea-level parameters results in different timescales to repository exposure and total loss. The magnitude of rise dictates the mechanism of repository failure at the time of initial exposure and during subsequent disruption.	Since the largest contributing uncertainties are those associated with political/policy decisions, it is not appropriate to assign probabilities to individual projections of sea-level change. Instead, a Reference Emissions Scenario is used, together with High and Low Emission Scenarios. These scenarios are used consistently throughout the ESC to explore the implications of the uncertainty. This uncertainty will reduce over the coming decades as we observe the global rate of transition away from fossil fuels, and wider research and observation of changes to climate and sea level. These will be reflected in the ESC within as part of its ongoing review cycle.
Conceptual model: The present-day coastal system is well understood, and there is confidence that major aspects of the system will not be impacted by climate change and sea-level rise. The coast is	With lower emissions and rates of sea-level rise the coastal processes and feedbacks are expected to be similar to those of the present day. However, the timescales to disruption of the repository are long compared with the	Ongoing characterisation of the coastal system using LLWR-specific coastal monitoring and review of outputs of the regional coastal monitoring programme builds confidence in the conceptual model,

expected to remain swash aligned, since this is dictated by the geography of the Irish Sea. The impact of higher emissions on storm frequency is particularly uncertain, and with rates of sea-level rise significantly greater than captured by the historical datasets, the response of the coastal system is uncertain. Responses are expected to be non-linear and are therefore difficult to project. Furthermore, some projected rates of sea-level rise in the High Emissions Scenario are significantly greater than those experienced in postglacial times and there remains uncertainty over coastal response. Evolution of a persistent foreshore/beach/cliff system is assumed, and while fundamental changes, such as development of a gravel barrier beach, can be conceptualised, they are difficult to predict.	historical dataset and prediction of long-term trends associated with a system in dynamic equilibrium is challenging. There are uncertainties when using the historical dataset to project future rates of erosion, both through simple extrapolation and when used to underpin more complex models, such as SCAPE and CRM. Compounding of uncertainties, biases and gaps in the historical datasets may impact projected timescales to disruption of the repository over such long timescales. With higher emissions and higher sea-level rise, the timescales to disruption of the repository are expected to be shorter. This slightly reduces the potential for compounding of uncertainties, biases and gaps, but the timescales are still long compared with the historical datasets, and the uncertainties, biases and gaps may be greater.	including the magnitude and frequency of storms and their impact on coastal erosion and beaches. Furthermore, the use of a range of different modelling approaches informs expert judgement about the rates of erosion and timing of repository impact. We are undertaking research to examine the response of analogue coasts following the last glacial period (the last period of rapid sea-level rise), to help underpin the relationship between sea-level rise and coastal erosion. Sea-level rise is anticipated to accelerate in the coming decades. Combined with our coastal monitoring programme, this will also help to underpin the relationship between sea-level rise and coastal erosion. Such aspects will be reflected in the ESC as part of its ongoing review cycle.
Sediment budget: The sediment budget defines the supply, persistence and fate of material in the coastal system, and is important in determining the ability of the beach to protect the cliffs from wave energy, and the persistence of the foreshore/beach/cliff system. While future	CRM is a sediment budget-based tool that explores feedbacks between sediment supply, beach size and erosion rate. Uncertainty over loss of sediment offshore or through clast attrition leads to uncertainty over beach size and erosion rate	Volumes of sediment lost from the beach have been explored through calibration of the CRM tool to hindcast recession observed in the last 20 years using measured parameters for sediment supply and sea-level rise. Furthermore, the use of a range of different state-of-the-art

sediment supply is reasonably well-constrained by the geological model, there is uncertainty over the rate of loss of beach-building material, which would be by a combination of offshore transport and clast attrition.		modelling approaches informs expert judgements about the rates of erosion and timing of repository impact.

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Nuclear Waste Services Limited
Pelham House
Pelham Drive
Calderbridge
Cumbria CA20 1DB
UK

t +44 (0)300 369 0000
w www.nuclearwasteservices.uk

Nuclear Waste Services

Where to find more information

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