Review of LLW Repository Ltd's 2011 environmental safety case: Site understanding

Issue 1, 15 May 2015

We are the Environment Agency. We protect and improve the environment and make it a better place for people and wildlife.

We operate at the place where environmental change has its greatest impact on people's lives. We reduce the risks to people and properties from flooding; make sure there is enough water for people and wildlife; protect and improve air, land and water quality and apply the environmental standards within which industry can operate.

Acting to reduce climate change and helping people and wildlife adapt to its consequences are at the heart of all that we do.

We cannot do this alone. We work closely with a wide range of partners including government, business, local authorities, other agencies, civil society groups and the communities we serve.

Published by:

Environment Agency
Horizon house, Deanery Road,
Bristol BS1 5AH
Email: enquiries@environment-agency.gov.uk
www.gov.uk/environment-agency

Further copies of this report are available from our publications catalogue:
www.gov.uk/government/publications
or our National Customer Contact Centre:
T: 03708 506506

Email: enquiries@environment-agency.gov.uk.

Executive summary

The Environment Agency is responsible for regulating the disposal of radioactive waste in England under the Environmental Permitting (England and Wales) Regulations 2010. As part of its current environmental permit LLW Repository Ltd had to submit an Environmental Safety Case (ESC) for the Low Level Waste Repository (LLWR) in west Cumbria to the Environment Agency by 1 May 2011 (the 2011 ESC).

This report covers our review of LLWR site understanding and evolution presented in the 2011 ESC. This includes the characterisation of the geological and hydrogeological setting of the LLWR and its environs, as well as the evolution of the LLWR over time. It also covers LLW Repository Ltd's environmental monitoring programme and the monitoring information provided within the 2011 ESC.

We consider the technical work and the overall quality of the 2011 ESC submission in the site understanding and evolution area to be of a high standard and based on sound science. The clarity of the environmental and geological information is generally good and the supporting information can generally be traced back to source documents. However, we had to request further documents not included in the original 2011 ESC submission to obtain enough information to conclude our review.

In our review, we have considered whether the 2011 ESC meets the principles and requirements set out in our guidance on requirements for authorisation of near-surface disposal facilities for solid radioactive waste (GRA). This guidance sets out what we would expect to see in an ESC.

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

We consider that LLW Repository Ltd has appropriately used site information to inform the development of geological and hydrogeological conceptual models and hydrogeological modelling. The company has appropriately identified the main uncertainties associated with the geological and hydrological environment and taken account of them in the groundwater flow and assessment models.

LLW Repository Ltd has used output from the most recently available climate change studies, combined with extensive characterisation and modelling of the Drigg coastline, to project that the LLWR is likely to start to be destroyed by coastal erosion after a few 100 to a few 1000 years from now. 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 indentifying 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.

LLW Repository Ltd has a comprehensive and high quality environmental monitoring programme in place. This programme covers all the relevant environmental media and demonstrates that the LLWR is not giving rise to unacceptable environmental impacts at the present time. The company uses output from the monitoring programme to support the conceptualisation and assessment of the LLWR, including the projection of future environmental impacts.

We consider that the environmental monitoring programme is capable of demonstrating compliance with the permit and assurance of radiological protection of members of the public throughout the period of authorisation. We will expect the company to make sure that the monitoring programme continues to evolve to meet the requirements of the environmental permit and support the ESC.

We consider that LLW Repository Ltd has appropriately used a wide range of environmental monitoring information in the 2011 ESC. However, as the LLWR develops, the company should, where possible and appropriate, work toward greater use of site-derived environmental monitoring data, as opposed to literature or modelled data, to inform and develop the ESC.

In summary, we are able to conclude that LLW Repository Ltd has adequately addressed those elements of the GRA of relevance to site understanding, site evolution and monitoring, for the purposes of the future permitting of the LLWR. However, we have identified a number of areas where further improvements should be made to ensure that the ESC continues to meet the requirements of the GRA.

Contents

1. Introduction

1.1. Introduction

The Environment Agency is responsible for regulating the disposal of radioactive waste in England under the terms of the Environmental Permitting (England and Wales) Regulations 2010 (EPR10) as amended (and before that was responsible under the terms of the Radioactive Substances Act 1993 (RSA 93) as amended). In accordance with government policy, we periodically review environmental permits for the disposal of radioactive waste. During this process we consider a wide range of information, including the conclusions from our reviews of the Environmental Safety Case (ESC) produced by the operator of the disposal facility concerned.

The Low Level Waste Repository (LLWR) near Drigg, Cumbria is the UK's primary facility for the disposal of solid low level radioactive waste (LLW). As a result of a major review of the LLWR ESC undertaken between 2002 and 2005, we included a requirement in the current LLWR environmental permit for the operator, LLW Repository Ltd, to 'update the Environmental Safety Case(s) for the site covering the period up to withdrawal of control and thereafter' (Schedule 9 Requirement 6). We received the updated ESC on 1 May 2011 (the 2011 ESC). We have subjected this ESC to a rigorous technical review using suitably qualified and experienced personnel.

The aims of the review were:

- to determine the adequacy of the 2011 ESC as a submission against Schedule 9 Requirement 6 of the current LLWR environmental permit
- to provide an Environment Agency view on the technical adequacy of the 2011 ESC
- to use as a major input to a forthcoming regulatory decision on permitting the LLWR for further disposal of radioactive waste
- to identify potential areas of improvement to the 2011 ESC, to guide LLW Repository Ltd

In our review, we have considered whether the 2011 ESC is based on sound science and engineering and meets the principles and requirements set out in the most recent environment agencies' guidance on requirements for authorisation (GRA) of near surface disposal facilities (Environment Agency et al. 2009). The GRA explains the requirements that we expect an operator to fulfil in applying to us for a permit to operate such a facility. It includes our radiological protection requirements and provides guidance on the nature of the ESC we would expect to see.

On 28 October 2013 LLW Repository Ltd made an application to the Environment Agency to vary the existing environmental permit under the EPR10 to dispose of further waste at the repository. This application covered an extended disposal area, which would allow sufficient capacity for the LLWR to accept a significant proportion of the UK's LLW predicted to be generated out to around 2130 (excluding lower activity LLW that could be diverted to other facilities). The application is in line with the proposals set out in the 2011 ESC, incorporating any subsequent modifications since the ESC submission. The proposal is to design, operate and close the facility in accordance with the 2011 ESC and subsequent changes described within the environmental permit application.

Our review of the 2011 ESC is intended to provide technical underpinning of our decision on LLW Repository Ltd's permit variation application. We will only permit further disposals at the LLWR if we are convinced that these disposals will not present an unacceptable risk to people and the environment. That is, the 2011 ESC needs to demonstrate that the short-term and long-term environmental impacts from past and proposed future disposals, taken together, will be acceptable.

1.2. The 2011 ESC submission

LLW Repository Ltd submitted the 2011 LLWR ESC to the Environment Agency on 1 May 2011. The 2011 ESC comprised the following hierarchy of documents:

- Level 0 - A non-technical summary, not aimed at regulators

- Level 1 - A single top level main report (143 pp) summarising the main arguments and the broad lines of evidence supporting them
- Level 2 - 16 topic reports (of 50 to 250 pp each) setting out in more detail the evidence to support the main arguments
- Key Level 3 - 95 underpinning reports (mostly 50 to 200 pp) identified by LLW Repository Ltd as being 'key'
- Other Level 3 - Several hundred other references referred to in the above documentation but not identified as 'key'

The Level 1 and 2 documents form the core of the 2011 ESC, with additional detailed information contained in Level 3 documents. During our review, we needed to extensively scrutinise many of the Level 3 documents in order to understand the safety arguments. The Level 0, 1 and 2 documents plus the 'key' Level 3 documents are available from relevant public registers and, at the time of writing and during our consultation period, from the LLW Repository Ltd internet site at: http://llwrsite.com/national-repository/key-activities/esc/esc-documentation/

LLW Repository Ltd has informed us that it is continuing to investigate potential options for the future design, operation and long-term management of the LLWR. We are also aware that the Nuclear Decommissioning Authority (NDA) and Site License Companies (SLCs) have been reviewing their procedures for estimating and reporting future LLW arisings to improve the accuracy of future inventory data. However, the scope of our review has comprised only the 2011 ESC as submitted, together with supporting documentation and further information provided up to and including the date of the environmental permit variation application made in October 2013. Any subsequent proposals to change the basis of the ESC will be addressed separately.

1.3. The review process

We have carried out a detailed technical review of the 2011 ESC. The review comprised an assessment of whether the ESC arguments, outlined in the Level 1 report, adequately address the requirements of the GRA and whether the evidence provided supports the arguments.

We have reviewed lines of evidence and underpinning information, judged by our suitably qualified and experienced reviewers to be of importance to the ESC, to the depth considered necessary to determine their validity, including tracing data and assumptions back to original empirical evidence. We have pursued other lines of evidence and underpinning information considered to be of less importance in less depth. We have completed a detailed review of the Level 1, Level 2 and important Level 3 documentation, also referring to other Level 3 documents to the extent that they underpin the ESC.

Environment Agency (2015a) provides further information on our approach to the review and the process we have used.

The primary test of the acceptability of the 2011 ESC as a whole, or of an individual document, was whether it meets Schedule 9 Requirement 6 of the current site permit and satisfies the relevant principles, requirements and guidance in the GRA. Where potential deficiencies or other issues were identified during our review, they were categorised as follows:

- A Regulatory Issue (RI) is a deficiency sufficiently serious that, unless or until it is resolved, we will either: (a) not grant a permit; or (b) grant a permit constrained by major limiting conditions (as distinct from information or improvement conditions) defined by us to mitigate the consequences of the RI.
- A Regulatory Observation (RO) is a deficiency not sufficiently serious to prevent our issuing a permit but sufficiently serious that, unless or until it is resolved, we will include an improvement or information condition in the permit requiring defined actions on defined timescales to resolve it (or to demonstrate suitable and sufficient progress towards resolving it). Related ROs may be grouped into a single improvement or information requirement. (We may also apply minor limiting conditions in the permit until it has been resolved.) An RO can become an RI if the condition is not met.

- A Technical Query (TQ) is a deficiency not sufficiently serious for us to require defined action by LLW Repository Ltd but sufficiently significant for us to request action. An individual TQ is unlikely to become an RO even if not addressed, but a number of unresolved TQs may accumulate into an RO.
- Any other further information or points of clarity considered to be worth requesting of LLW Repository Ltd are designated as Minor Comments. LLW Repository Ltd was requested, but not required, to provide responses to these to enable us to conclude our review of the 2011 ESC. However, LLW Repository Ltd did provide responses whenever requests for further information were made.

For each RI, RO and TQ we have generated an Issue Resolution Form (IRF), which records and tracks the issue and its resolution. IRFs are detailed records of concerns raised as part of our review of the 2011 ESC. Each IRF defines one or more actions. We have expected LLW Repository Ltd to provide a substantive response to the action(s) specified on the IRF by a specified date(s).

The IRFs form a substantial element of our review output. LLW Repository Ltd has provided responses on each IRF; where appropriate this may be a summary of the response, referring to more detailed information in supporting documentation. Each IRF also records our evaluation of the response. An issue has only been closed out when we have determined that the response from LLW Repository Ltd adequately addresses it. Where appropriate, we raised further actions or queries so we could close the IRF. All IRFs have now been closed.

We recognise that the 2011 ESC is a complex submission involving a wide range of technical assessments that will evolve and improve in the future as technology and understanding advances. Certain details will also be developed further as the site advances, for example towards construction of the final engineered cap over the waste. Within our review we therefore identify important areas which we believe will benefit from further work, development or clarification in the future. These areas are identified as Forward Issues (FIs). These represent areas of work that we believe it is important for LLW Repository Ltd to progress as part of its forward improvement plan. FIs address areas where we expect continued improvement in the ESC and its implementation. We will require LLW Repository Ltd to engage with us on these FIs, to put in place formal mechanisms to track and address them and, as necessary, incorporate work to address them in its forward programmes of work and report to us on progress and when it believes the FIs have been fully addressed. We will expect the outcome of FIs to be considered within any subsequent updates to the ESC.

Throughout the review, we also made a number of specific recommendations to LLW Repository Ltd. Recommendations represent areas where we see scope for possible improvement or development, but which are relatively minor in nature relative to FIs. These recommendations are numbered and highlighted in this document. As a matter of good practice we expect LLW Repository Ltd to address these recommendations and will expect a mechanism to be put in place to track them.

It is important to note that these FIs and recommendations do not represent the only areas of work that we will expect LLW Repository Ltd to progress and are not intended to represent a comprehensive scope for forward work. We will require the company to develop its own forward programme of work as necessary to maintain and improve the ESC; our FIs and recommendations should only form part of that programme. LLW Repository Ltd's forward programme of work must be informed by a wide range of inputs, for example monitoring data, research and development, improvements in technology and continuous improvement.

This report is necessarily focused on the negative, bringing out areas where we have raised concerns, or have remaining concerns, or expect further action or permitting requirements. We do not necessarily comment on areas we are content with and we do not list everything we have reviewed. The length of discussion on any particular topic may depend on the degree of interaction between us and LLW Repository Ltd and does not necessarily reflect the significance of the issue. However, we have made positive comments where we believe that the treatment of issues represents good practice.

1.4. ESC review deliverables

The output from our review of the 2011 ESC is a series of review reports that will provide technical underpinning to future permitting decisions. The document hierarchy is illustrated in Figure 1.

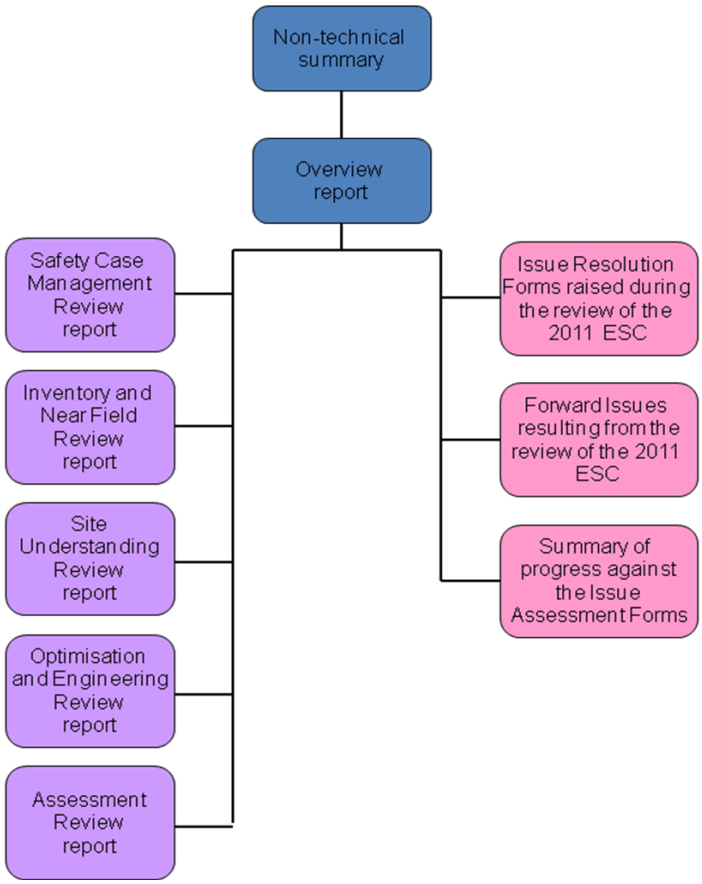

Figure 1 Hierarchy of documents supporting the Environment Agency review of the 2011 ESC

The main document is the overview report of the technical review (Environment Agency 2015a). It provides our conclusions on the extent to which LLW Repository Ltd's 2011 ESC demonstrates to our satisfaction that existing and proposed future disposals meet the requirements set out in the GRA, as well as whether Schedule 9 Requirement 6 has been met satisfactorily. The overview report includes background information on the history of the LLWR and regulatory requirements. It also describes our review process in greater detail.

The overview report is supported by 5 technical review reports, which provide more detailed conclusions on the technical adequacy of the ESC as a basis for permitting future disposals. These reports cover the following topic areas: Safety Case Management (Environment Agency 2015b); Inventory and Near Field (Environment Agency 2015c); Site Understanding (this report); Optimisation and Engineering (Environment Agency 2015d); and Assessment (Environment Agency 2015e). The IRFs resulting from each of the topic area reports are collated in a standalone report (Environment Agency 2015f).

Forward Issues that are raised as a result of our review of the 2011 ESC are also collated in a separate report (referenced as ESC-FI-xxx) (Environment Agency 2015g). We will agree with LLW Repository Ltd when and how it addresses these issues through our normal regulatory interactions and will track progress made to resolve them.

We documented concerns from our review of the previous LLWR Operational Environmental and Post-Closure Safety Cases (the 2002 ESCs; British Nuclear Fuels Ltd (BNFL) 2002a,b) on Issue Assessment Forms (IAFs), which are similar to the IRFs. We report our review of LLW Repository

Ltd’s progress in addressing actions raised in the IAFs in Environment Agency (2015h). Any actions that we consider have not been fully addressed in the 2011 ESC are taken forward in the FIs or recommendations.

We have also prepared a non-technical summary of our review of the 2011 ESC (Environment Agency 2015i).

Together the documents describing the review of the 2011 ESC summarise the findings of our review and provide information to support consultation on our draft decision about the future permit for the LLWR.

We welcome any comments on our review findings. Such comments could be provided in response to our forthcoming consultation on permitting the LLWR.

2. Site understanding

2.1. Overview

This report is one of 5 technical assessment reports that support the overview report of our review of the 2011 ESC and cover the main topic areas of the ESC in more detail. It considers LLW Repository Ltd's understanding of the LLWR and its environs as presented in the 2011 ESC and further evidence provided up to and including submission of LLW Repository Ltd's environmental permit variation application on 28 October 2013. Our review covers 3 distinct areas: site investigation and characterisation; evolution of the site; and monitoring. We have reviewed both the characterisation of the site and the use of characterisation information in the 2011 ESC performance assessment.

Our review has focused on the 2011 ESC Level 2 and Level 3 reports. Where these reports did not contain sufficient information, we requested further documentation from LLW Repository Ltd.

We raised a series of IRFs as part of our review. This was to challenge, clarify or seek further evidence in areas where we considered the case submitted fell short, for example, where we considered that the requirements of the GRA were not fully addressed, or where we took the view that technical arguments or conclusions required further evidence to support them. The IRFs are summarised in Appendix 1 of this report and presented in full in a separate report (Environment Agency 2015f).

LLW Repository Ltd satisfactorily addressed all the IRFs raised in the site understanding area during the course of our review and we have closed them. Nevertheless we have identified a series of recommendations and FIs where we consider there is scope for LLW Repository Ltd to make further improvements or pursue developments to the ESC in the future. Whether we made a recommendation or raised a FI depends on the environmental consequences in the absence of any further work. Tables summarising the recommendations and FIs are respectively presented in Appendix 2 and Appendix 3 of this report. We also assessed whether the information presented was sufficient to address technical issues that we raised previously in our assessment of the 2002 ESCs (Environment Agency 2005a). A summary of how LLW Repository Ltd has addressed these issues can be found in a separate report (Environment Agency 2015h).

The following sections detail our review, focussing on those areas we deemed important to the 2011 ESC. We highlight why we raised certain issues with reference to the GRA requirements and indicate whether we consider relevant requirements or issues have been adequately addressed.

2.2. Site investigation and characterisation

The geology of the region around the repository comprises Quaternary sediments that overlie Triassic Sherwood Sandstone bedrock. The Quaternary sediments consist of a wide range of material types of significantly different properties and exhibit complex spatial relationships. These relationships determine the behaviour of groundwater (and to an extent any contaminants) in the vicinity of the LLWR.

The area around the LLWR has been extensively investigated. Approximately 650 site investigation boreholes have been drilled on and around the LLWR. These boreholes have highlighted the complexity and heterogeneous nature of the Quaternary sediments underlying the LLWR. Further information has been obtained during site construction work (for example, excavations for trenches and vaults) and exposures in the cliffs on Drigg beach.

LLW Repository Ltd present revised conceptual models of the geology and hydrogeology in the 2011 ESC based on a re-interpretation of existing data, as well as making use of data that have arisen from recent site projects (for example, Vault 9 construction and a coastal geophysical survey). This work built on the company's 2008 submission on site understanding that was

prepared in response to Schedule 9 Requirement 2 of the current environmental permit[1] (LLW Repository Ltd 2008b, as reviewed in Environment Agency 2009a and b).

Three major site investigation projects have taken place since 2008:

- geological logging of Vault 9 excavations (Smith 2009)
- drilling of 14 'Stage 6' boreholes for use as groundwater monitoring wells (URS 2009)
- coastal geophysics survey and interpretation (Halcrow 2010a)

We are satisfied that LLW Repository Ltd has used appropriate site investigation techniques, suitably qualified and experienced personnel and British Standard logging/sampling methodologies where appropriate in carrying out these investigations. These studies, along with environmental monitoring data, informed the development of the site conceptualisation presented in the 2011 ESC.

We recognise that LLW Repository Ltd has carried out data quality review exercises and has been able to allocate a level of confidence to the geological and hydrogeological information. LLW Repository Ltd should continue to review the quality and appropriateness of past borehole data and make sure it is used appropriately to inform future updates of the ESC (**Recommendation SUE1**).

The area of land between the western edge of the LLWR and the coast is recognised as the main pathway for groundwater and contamination flow from the repository to the coast and potential receptors. This area of land is also predicted to be subject to coastal erosion at some point in the future. It is important that the 2011 ESC appropriately takes into account the characteristics of this area of land.

LLW Repository Ltd has carried out a substantial site investigation and geophysics programme adjacent to and within the area between the LLWR and the coast. This information has significantly increased the understanding of the shallow drift sequence in this area. In particular, the coastal geophysics investigation carried out in 2010 has improved understanding of the relationship between the Quaternary drift and underlying geology. LLW Repository Ltd has effectively used the gathered information to inform both the hydrogeological model and the models developed to project coastal recession (see Section 2.3.3). As understanding and technology related to geophysical surveying increases, we expect LLW Repository Ltd to take this into account and to undertake further geophysical surveys or reprocess existing information as appropriate, to further inform site geological understanding (**Recommendation SUE2**).

Because of the inherent complexity of the geological sequence between the LLWR and the coast, even with the significant improvements in the geological characterisation over recent years, the level of geological understanding of the complex Quaternary sequence remains low, particularly on a small scale. As a result, although understanding of groundwater flow and transport on a large scale is good, there remains a degree of uncertainty on a smaller scale. However, we consider the conceptualisation is sufficient to inform the 2011 ESC. To significantly improve the conceptualisation of the geology and hydrogeology in this area a large number of further boreholes would be required and we consider that this is disproportionate. Much of the area between the LLWR and the coast is designated as a Special Area of Conservation (SAC) and Site of Special Scientific Interest (SSSI), making further intrusive investigation challenging and potentially detrimental to the surrounding environment. To continue to reduce uncertainties, we recommend that LLW Repository Ltd looks for opportunities to undertake further opportunistic investigations, taking into account access constraints and without compromising the integrity of the protected environment. This might, for example, include re-assessment of existing information and the

[1] Schedule 9 Requirement 2 of the current environmental permit required LLW Repository Ltd to provide us with a comprehensive review of national and international developments in best practice for minimising the impacts from all waste disposals on the site by May 2008. This included a review of options for reducing the peak risks from disposals of solid waste on the site, where those risks arise from potential site termination events (e.g. coastal erosion and glaciation) and potential future human action.

construction of boreholes immediately adjacent to, but not within, the protected sites (**Recommendation SUE3**).

2.2.1. Geological understanding

The geology of the LLWR and its environs is presented within the Level 2 Hydrogeology report (LLW Repository Ltd 2011a) and is based on an updated review of the geology carried out to support the 2011 ESC (Michie et al. 2010). The review focused on the Quaternary sediments on which the LLWR is located (and to a lesser extent the upper sandstone), as the heterogeneous nature of these deposits has significant implications on hydrogeology, contaminant transport through the sub-surface environment and on coastal erosion. The geological conceptualisation was used to support the development of a 3D geological computer model (Smith 2011) and to inform the hydrogeological conceptualisation, engineering design and performance assessment.

Michie et al. (2010) used discrete lithofacies units to characterise the shallow geological environment. The lithofacies units were created by grouping together units with similar lithological properties, on the assumption that these units would also have similar hydrogeological properties. This approach moved away from the stratigraphic approach used in the 2002 Post-Closure Safety Case (PCSC) (BNFL 2002a, b), placing a greater emphasis on the descriptive analysis of the sequence.

The principal lithofacies units and the hydrogeological conceptual model are illustrated in Figure 2.

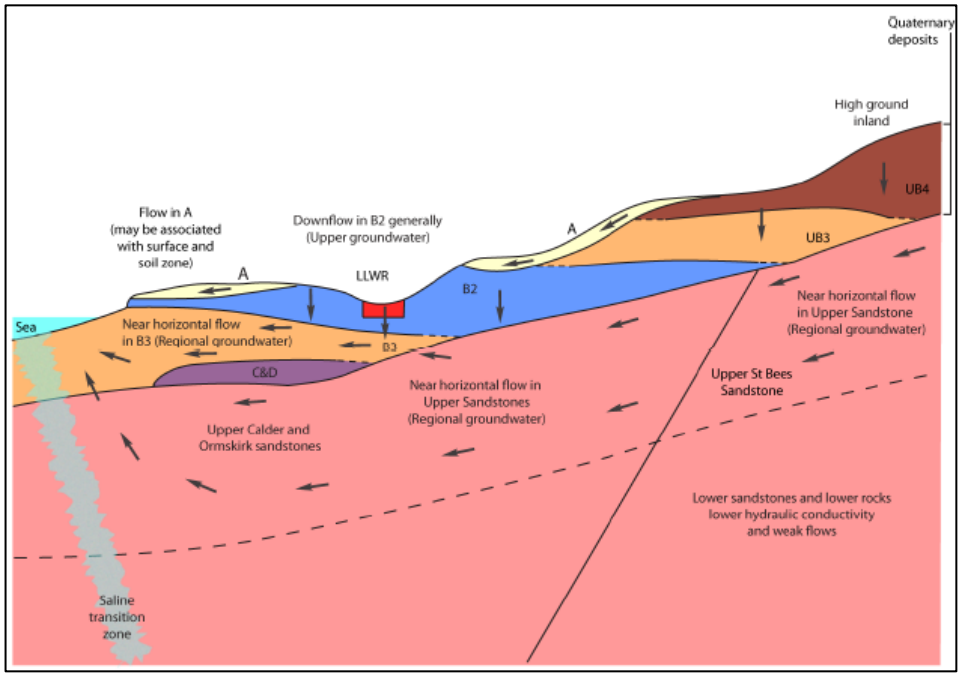

Figure 2: The hydrogeological conceptual model of the LLWR presented in the 2011 ESC. Schematic east to west section (the arrows show the direction of flow and not the velocity) (Jackson 2011)

The lithofacies units comprise:

- Unit A: upper Quaternary deposits including soil and made ground
- Unit B2[2]: a sequence of inter-bedded glacial tills, sands and gravels
- Unit B3: dominantly composed of permeable to very permeable thick sand and gravel deposits

[2] Lithofacies Unit B1 only occurs off-shore.

- Unit C: a laterally discontinuous unit consisting of till as well as sands, gravels, silts and clays, that is less permeable than B3
- Unit D: older Quaternary deposits that are variable in composition and laterally discontinuous

LLW Repository Ltd considers that the transition from Upper to Regional groundwater is generally coincident with the interface between lithofacies Unit B2, that has low vertical hydraulic conductivity and lithofacies Unit B3, that has a relatively high conductivity (LLW Repository Ltd 2011a).

We consider that the lithofacies approach used to inform the 2011 ESC represents an improvement over previous stratigraphic classifications. The lithofacies approach recognises the importance of understanding the physical properties of the underlying geology and has allowed an improved linkage to be made between the geological interpretation and understanding of the hydrogeological environment. Because of the heterogeneous nature of the lithofacies units, it remains important that hydrogeological models can take account of localised groundwater flow characteristics associated with the presence of low permeability units within high permeability units.

We note that the development of the geological conceptual model and the 3D geological model in parallel during 2010 led to inconsistencies between the 2 models and the need for a further iteration of the 3D model in September 2010 (Smith 2011). However, the earlier May 2010 3D geological model was used for the development of the hydrogeological model, necessitating a retrospective assessment of the implications of updating the 3D geological model (Hartley et al. 2011a). Hartley et al. (2011a) state that the September 2010 3D geological model is not an improvement over the May 2010 model in certain ways, as it contradicts some hydrogeological data (for example, with respect to the thickness of lithofacies B2, monitored water levels and site observations). We note that the number of iterations taking place on the 3D geological model in a relatively short period of time led to some loss of clarity in the 2011 ESC documentation and inconsistencies between information used in the latest versions of the conceptual models and hence the groundwater flow models. This loss of clarity took place immediately prior to the submission of the 2011 ESC and is not typical of LLW Repository Ltd's overall hydrogeological and geological model development and assessment process.

During our review of the 2011 ESC, LLW Repository Ltd has taken steps to enhance hydrogeological modelling expertise within the ESC Team. We support this move which we consider will help with the future planning of work and the robustness of the company's intelligent customer role. Utilising this enhanced intelligent customer capability we would like to see LLW Repository Ltd considering improvements to how it plans work tasks, for example such that relevant workstreams are carried out sequentially where practicable (noting that they cannot always be) and avoiding issues such as those referred to above related to the 3D geological models. In future updates of the ESC, we expect to see clear identification of the models being used and demonstration that they have clear audit trails (**Recommendation SUE4**).

As part of our work on the repository Habitats Regulations appropriate assessment (Environment Agency 2014a), we sought clarification on the extent of any changes to the surface and groundwater system in the Drigg Dunes adjacent to the repository, resulting from the proposed development of the LLWR (Environment Agency 2014b). The 2011 ESC assumes that the shallow (upper) groundwater within the dune system (and the evolving dune system in future) will be isolated from the regional groundwater in the B3 lithofacies unit due to the dominant vertical groundwater flow. We agree that the geometry and discontinuous nature of the dune deposits mean that they would be unlikely to act as a viable groundwater pathway for discharges from the LLWR. However, the presence of the dunes may change the amount and rate of vertical recharge of the lower glacial geologies that form the main groundwater pathway, although the majority of groundwater flow in the deeper geologies is derived from recharge zones significantly upstream (to the east) of the site. We therefore recommend that any observed or predicted changes in the nature and extent of the dunes is considered in future reviews of the ESC hydrogeological models[3]

[3] Our expectation for future coastal and dune monitoring are described in ESC-FI-019.

(**Recommendation SUE5**). As a result there is a level of uncertainty associated with the groundwater transport within the Quaternary geology. This is appropriately taken account of in the hydrogeological models used in the 2011 ESC.

LLW Repository Ltd identified a number of glaciotectonic features exposed during the construction of Vault 9. These features were associated with small-scale contemporaneous faulting of glacial drift materials. The presence of small scale glaciotectonics within the Quaternary sequence is accounted for in the geological model by attributing uncertainty to the spatial extent of high permeability (sand/gravel/cobble) lithologies. A post-2011 ESC assessment of the effect of faults on the hydrogeology at the LLWR included an assessment of glaciotectonic faulting (Woollard and Jackson 2012). We consider that the presence of glaciotectonic features increases the complexity of the Quaternary geology and flow paths, but does not require specific conceptualisation within the groundwater models due to their relatively small scale within the superficial materials.

We acknowledge that both the hydrogeological and geological models and associated assessments sought to characterise the heterogeneous nature of the superficial glacial deposits, resulting in an improved representation of the geological and hydrogeological environment in the 2011 ESC and subsequent documentation. Even with these improvements in understanding, LLW Repository Ltd acknowledges that uncertainty remains (LLW Repository Ltd 2013a). Because of the significance of the superficial glacial materials in both the hydrogeological and coastal erosion assessment it is important that the remaining uncertainty is appropriately communicated and taken account of in the ESC. Other than the points discussed above we are satisfied that this is the case.

There is an important link between the shallow geological information collected to support groundwater assessment and the coastal landscape assessment used to inform the modelling of the coastal evolution sequence. This commonality is not fully recognised in the 2011 ESC and may benefit from increased integration in future updates of the ESC. We have asked LLW Repository Ltd, that as part of its' monitoring of coastal erosion, it undertakes surveys of the exposed cliff and shoreline either after extreme storm events or at regular intervals (ESC-FI-019). As the shoreline is eroded, we recommend that geological information, derived from the exposed cliffs, is considered in the repository geological model where appropriate (**Recommendation SUE6**).

Overall, LLW Repository Ltd has demonstrated a good and sufficient understanding of the geological setting of the LLWR. This has been used appropriately to inform the assessment models used throughout the 2011 ESC. We expect to see the continuation of an iterative approach to the update and review of the LLWR geology as part of the ongoing maintenance and development of the ESC.

2.2.2. Hydrogeological understanding

The updated hydrogeological conceptualisation of the LLWR and its environs is presented in LLW Repository Ltd (2011a). However, we needed to extensively draw from information in the Level 3 reports for our review, especially the updated hydrogeological conceptual model report (Jackson 2011). In general, we consider that the 2011 hydrogeological conceptualisation is an improvement over the 2002 conceptualisation and in particular we consider that the characterisation of the heterogeneous hydrogeological properties of the Quaternary deposits has been much improved. However, uncertainties remain and are discussed further below.

LLW Repository Ltd identifies 5 'key uncertainties' in its long-term radiological assessment (Section 10.3 of LLW Repository Ltd 2011b). Two of the 5 'key uncertainties' relate to hydrogeological conceptualisation 'the effective dilution factor of water entering the Regional Groundwater from the repository, linked to the degradation of the engineered features'; and 'uncertainties related to the heterogeneous nature of the Quaternary sediments and consequent flow path characteristics and dilution'. We queried this issue in IRF ESC-RO-SUE-007. In response, the company provided examples of the main uses of monitoring data in the 2011 ESC and the potential approaches to addressing some of the key uncertainties in the 2011 ESC (Baker and Cummings 2012), that gave us sufficient information for the purpose of completing our review of the 2011 ESC. We raised a FI to request more information about how LLW Repository Ltd intends to develop the forward monitoring programme to address key uncertainties in the ESC (ESC-FI-005). To assist in the provision of the objectives described in ESC-FI-005, we recommend that the company includes where possible, the reduction of the remaining uncertainties in the repository conceptualisation as

a site investigation objective (**Recommendation SUE7**). Examples include dilution factors and heterogeneity.

The 2011 ESC notes the potential for incised channels infilled with gravel within B3 to act as fast pathways. Jefferies (2009) states that the potential hydrogeological significance of the channels is still uncertain. According to Hartley et al. (2011a), hydrogeological information (low horizontal gradients and high hydraulic diffusivities) suggests that these channels are extensive, at least providing a rapid hydraulic connection between the shore and the site. Jefferies (2009) states that the impact of large-scale features such as channels could be treated deterministically in variant calculations to assess their potential impact on post-closure performance. However, this is not presented in the 2011 ESC, although increased flow rates in B3 are considered in the probabilistic groundwater pathway assessment calculations. We are therefore satisfied that the potential effects of this phenomena are appropriately bounded within the current assessments but recommend that LLW Repository Ltd further investigates the potential effect of incised infilled channels acting as fast groundwater pathways (**Recommendation SUE8**).

Jackson (2011) acknowledges that flow in the Ormskirk Sandstone makes a significant contribution to regional groundwater flow, however, there is uncertainty regarding the likelihood of contamination reaching the upper sandstone. Although new boreholes were drilled into the upper sandstone, no data are presented in the 2011 ESC that indicate whether contamination is likely to reach the upper sandstone. Although 'hydraulic communication with the Ormskirk Sandstones is expected to be limited due to the intervening semi-permeable lithofacies unit C' (Hartley et al. 2011b), there appears to be a potential for some flow between the sandstone and unit B3. We accept that the significance of this uncertainty to the hydrogeological assessment is likely to be low. However, we also consider that this is an uncertainty that LLW Repository Ltd should continue to investigate with a view to reducing uncertainty and better informing conceptual models. We therefore recommend that the company continues to review the importance of contaminant migration in the upper sandstone. This should include consideration of the relative importance of fracture flow versus matrix flow in the upper sandstone, as well as the potential effect of faults on flow within the upper sandstone[4] (**Recommendation SUE9**).

An elevated groundwater mound is present on the south west boundary of the LLWR. In the 2011 ESC, LLW Repository Ltd states that it is unclear whether this mound is part of the Upper or Regional Groundwater (LLW Repository Ltd 2011a). The company has carried out further hydrogeological characterisation of the mound and groundwater dilution rates since the submission of the 2011 ESC. At the time of writing, we have not yet received or reviewed the outcomes of this investigation. Any applicable outcomes from these investigations should be incorporated into future updates of the ESC. If the groundwater mound is found to be the result of measurement errors, then we would expect the site hydrogeological understanding to be updated in line with this (**Recommendation SUE10**).

As part of the ongoing maintenance of the ESC, we expect LLW Repository Ltd to consider the requirements to store, retrieve and use the geological and hydrogeological information that was used to inform the 2011 ESC and any data collected in the future. It is essential that the geological information, as well as customised model codes, are maintained and managed in such a way to ensure the information remains traceable, applicable and available.

We conclude that a good hydrogeological understanding of the setting of the LLWR has been demonstrated within the 2011 ESC and that this has appropriately informed the hydrogeological conceptualisation used within the 2011 ESC.

2.2.3. Hydrogeological modelling

The updated hydrogeological modelling of the LLWR and its environs is summarised in the Level 2 Hydrogeology report (LLW Repository Ltd 2011a). However, we focussed our review on the

[4] We note that, subsequent to the submission of the 2011 ESC, LLW Repository Ltd carried out an assessment of the effect of geological faults on the hydrogeology in the vicinity of the LLWR. At the time of writing, we have not reviewed this work.

underlying Level 3 hydrogeological modelling report (Hartley et al. 2011a), to allow us to fully understand the content of the assessment and the underlying assumptions.

The 2010 hydrogeological model was based on the May 2010 geological model that was later updated in September 2010. However, we accept the conclusions of Hartley et al. (2011a) that the implications of this change are not significant. As noted under Section 2.2.1, we expect improved planning of future work to ensure consistency between linked workstreams and models (see Recommendation SUE4).

Approach to hydrogeological modelling

The hydrogeological modelling involved the development of numerical models using the ConnectFlow software package (developed by AMEC) to establish a quantitative understanding of groundwater flow patterns (Hartley et al. 2011a). Modelling was carried out both on a regional and also at a site scale. Additionally, a compartmental flow model was developed to represent groundwater flows using the GoldSim software package that was then implemented within the 2011 ESC assessment calculations.

Both ConnectFlow and GoldSim are used by other radioactive waste management organisations and were appropriately used by LLW Repository Ltd in the production of the 2011 ESC. In an audit of the groundwater assessment models we gained confidence in the quality systems and procedures used to develop, populate and maintain the groundwater modelling software (Fairhurst 2013) (see further detail in Section 2.2.8). We concluded that LLW Repository and their contractors had robust and comprehensive quality assurance systems in place to develop and manage groundwater models. We are assured that both the 'off-the-shelf' and customised models have been developed and applied appropriately using a combination of site derived information and generic hydrogeological algorithms.

The deployment of modelling at different scales of resolution is commonplace in hydrogeological studies as it enables components (for example, the regional groundwater flow system and the disposal facility groundwater flow system) to be separated and represented efficiently to meet the modelling objective. This approach is commonly viewed as good practice. However, we consider that the modelling hierarchy used within the 2011 ESC is not as clearly described as it could be and so does not readily facilitate a clear understanding of the modelling objectives or clearly demonstrate the appropriateness of using both regional and site-scale modelling and a compartmental flow model.

In our review of the 2002 ESC, we raised an IAF that asked LLW Repository Ltd to update the hydrogeological modelling approach to take account of the effects of the construction of future vaults on contaminant migration (GEO_019.1 and GEO_019.2). As a result, the 2011 hydrogeological model is constructed in such a way as to take account of the predicted vault construction sequence. The model is able to take account of the timing and location of the discharge, including the interaction with past discharges from the trench disposals. Because of the complex nature of the near field superficial geology and remaining uncertainty in the response of the shallow groundwater to the construction of the both the vaults and perimeter cut-off walls we recommend that the effects of the construction of future vaults on contaminant migration and the behaviour of the existing trench contamination plume should continue to be reviewed throughout the construction and restoration sequence (**Recommendation SUE11**).

The ConnectFlow and GoldSim models take account of the behaviour and properties of the individual elements of the repository engineering and waste mass. This capability has allowed LLW Repository Ltd to model the impact of repository construction and the evolution of the repository system beyond the period of authorisation. We welcome this aspect of the modelling and consider it essential in the demonstration of safety. By necessity the representation of the vault and trench waste mass in the models has been greatly simplified and may not reflect the small and medium scale behaviour of leachate within the waste mass. Because of the importance of this aspect of the hydrogeological model we would like to see consideration of ongoing improvements in the characterisation and functionality of small and medium scale behaviours, as well as continued alignment of the model with the engineering design, with the specific objective of improving the conceptualisation and modelling of the as built trench and vaults (**Recommendation SUE12**).

In our review of the 2002 ESC we concluded that future ESCs should incorporate an improved structure and clarity of reporting of hydrogeological characterisation and modelling work (IAF GEO005.1, IAF GEO_0021.1 and IAF GEO_021.2). Despite improvements in the 2011 ESC, we consider that the linkage between the site conceptualisation data, the geological and groundwater flow models and the assessment models could still be better documented. We queried aspects related to this in ESC-RO-ASO-007 and, in response LLW Repository Ltd described the role of individual groundwater models and illustrated the links between models and the model hierarchy (Shevelan 2013a). The information presented in Shevelan (2013a) greatly increased the clarity of the modelling approach and the role of each model in site understanding. We will expect future updates of the ESC to similarly improve presentation of models used for site understanding, to improve the clarity of documentation (**Recommendation SUE13**).

Overall, we conclude that an appropriate and robust approach has been used in developing the hydrogeological models used in the 2011 ESC. However, due to the complex nature of the superficial geology it is important that the geological and hydrogeological models continue to be informed by site derived information.

Hydrogeological modelling to support repository engineering design

The 2011 ESC describes the long-term evolution of the LLWR during and after the degradation of the engineered barrier system. To mitigate radiological impacts associated with the possibility of overtopping of leachate into the near surface environment, the vault design includes a basal drainage layer below the base of future vaults. The basal drainage layer could either comprise in-situ granular superficial geologies (typically fluvio-glacial gravels) or engineered granular materials with similar flow properties. This is designed to channel any leachate downwards into the deeper geological environment away from the local biosphere.

In our Optimisation and Engineering review report (Environment Agency 2015d) we discuss the uncertainty associated with the functionality of the engineered basal drainage layer and the in-situ geological material in providing a sufficient pathway for any leachate in the future, following cap degradation and failure. We will expect LLW Repository Ltd to demonstrate that the in-situ material between the vault and the cut-off wall, the engineered basal drainage layer, or a combination of the two is sufficient to provide any necessary leachate drainage to prevent overtopping. This demonstration must take account of any uncertainties over the geology and the drainage media's performance over the long timescales that it must remain effective. We also discuss the ability of the hydrogeological models to take account of this uncertainty. We consider that the mechanism for the mitigation of overtopping is conceptually valid, but consider that it will require further demonstration before construction of further vaults or the start of final capping. We will expect this demonstration to include collection of appropriate site-derived geological and hydrogeological information from the base and sides of future vaults and increased model functionality to characterise the overtopping sequence. Associated with this, we will expect an improved understanding of the behaviour and functionality of any engineered basal drainage system; it's evolution over extended periods and its combined ability, alongside the in-situ geology, to achieve adequate drainage and avoid overtopping. We further detail our expectations in ESC-FI-023. Where possible, site-derived permeability testing should be considered, such as soakaway and packer tests.

To better inform the conceptualisation of the overtopping sequence and demonstrate that the required functionality can be achieved, we recommend that the hydrogeological characteristics of the area of land between the vault and cut-off wall are investigated further (**Recommendation SUE14**).

Calibration

Calibration of the numerical hydrogeological models was carried out by LLWR Repository Ltd against collated datasets that included groundwater levels, streamflow gauge records and measured concentrations of tritium in groundwater (Hartley et al. 2011a).

Time-averaged calibration targets for groundwater levels were derived from monitoring data for the period between 1995 and mid-2008 (that corresponded to the capping of Trench 7 and the excavations for Vault 9). It is unclear why a longer period of monitoring data was not used (noting

that it would not have been practicable for LLW Repository Ltd to use all the data up until the data freeze in 2010). A larger dataset would allow the regional groundwater flow system to be studied over an extended period and facilitated understanding of how the construction of the as-built engineered features of the disposal facility may affect local groundwater conditions, as well as how this understanding could be applied to a consideration of the potential impacts of further disposal vaults and closure engineering. For future updates of the ESC we recommend that a longer period of monitoring data is used to calibrate and build confidence in numerical models developed to support safety assessments (**Recommendation SUE15**).

The modelling study used the concept of slope and level plots as an aid to interpreting the fit of parameter combinations and reported in some detail the work done to understand and explain the behaviour shown by the models during calibration iterations at certain locations and/or features. However, any quantitative tests that were applied to aid in guiding model calibration are not discussed in the reporting of the calibration exercise. We recommend that future model calibration recognises and uses quantitative tests as part of the calibration process and summarises them appropriately (**Recommendation SUE16**).

Judgements on which parameterisation gives the most appropriate fit to the observed data are based on assertions made on the qualitative interpretation of graphical plots, with limited consideration of numerical tests. For example, the Base Case is stated to produce a reasonable match at site boreholes for the vertical gradient (that show a difference of around 5% from the observed values) but not for the groundwater levels (that show a difference of around 25% from the observed values), so a match acceptable for the purposes of the studies must be assumed to be somewhere between these values. Similarly, the consideration of sensitivities to representing groundwater behaviour at a regional scale is also done using qualitative judgements to evaluate the match of modelled slope and level data with values derived from observations. The approach used is adequate, but LLW Repository Ltd should consider use of quantitative analysis to support the qualitative interpretation and to build further confidence in future models (**Recommendation SUE17**).

Calibration of the numerical hydrogeological models was dominated by modification of hydraulic conductivities, within specified ranges, to improve the fit of models with observed data. With reference to the data presented by Hartley et al. (2011a), we note that the correlation between calibrated model data and site data appears reasonable for lithofacies units C and D and the upper sandstone. However, the model values for B3 (in particular for sand and gravel) seem high, whilst the model vertical conductivity for B2 seems very low compared with site data. It is also not clear why consideration of the effects of ranges in other important input parameters such as hydrologically effective rainfall (HER) or cap infiltration (due either to their spatial variability or uncertainty) are not included in the calibration exercise. We recommend that LLW Repository Ltd should clearly substantiate its choice of parameters and data ranges used in the calibration of future hydrogeological models (**Recommendation SUE18**).

We accept that a significant quantity of new data (from locations both on and off site) have been obtained since the submission of the 2002 ESCs. This information has been used to update the site water balance (Towler et al. 2007) and estimate baseflow (Henderson 2008). Because of the remaining levels of uncertainty in the geological and hydrogeological properties of the repository and its environs, we recommend that LLW Repository Ltd ensures that an objective of the routine site environmental monitoring programme is the systematic collection of hydrological and hydrogeological data to support future refinements of the ESC hydrogeological models (**Recommendation SUE19**).

The modelling study explicitly recognises that there may be more than one set of parameters that give an acceptable fit to the calibration data for a particular conceptual model. However, there is no attempt to test other parameter sets that may prove equally valid with the chosen conceptual hydrogeological model. In future updates of the ESC, LLW Repository Ltd should provide a way of building confidence that there are no other equally valid model parameterisations that would significantly impact the ESC (**Recommendation SUE20**).

Overall, we consider that the calibration of numerical hydrogeological models is adequate for the purpose of the 2011 ESC, but have noted a number of areas for possible improvement in the future.

Groundwater flow modelling

Flow in the unsaturated zone is represented using relative permeability, hydrostatic pressure and saturation data. This approach introduces more realism, but also complexity, compared to simpler approaches previously adopted. Conversely, characteristic functions have not been derived for the specific material types expected within the trenches, vaults and surrounding geological media. This is despite the fact that significant differences may be expected, given that the trenches are located in low permeability clays and the vaults will potentially be located on high permeability granular materials. Other hydrological processes that may be important in understanding unsaturated zone flow (for example, hysteresis) have not been considered and it is not clear how any effects of open air waste disposals and emplacement, or the effects of capping have been considered in determining initial conditions. Although we consider the overall representation of flow in the unsaturated zone to be acceptable for the purposes of the 2011 ESC, in future updates of the ESC, we expect this representation in the hydrogeological flow model to be better underpinned, taking into account the variability of the geological media in the unsaturated zone and changes brought about by the trench and vault development and restoration sequence (**Recommendation SUE21**).

The ConnectFlow numerical modelling places significant emphasis on particle tracking exercises to delineate the extent of potential contaminant migration. The numerical simulations are stated to be consistent with site-derived monitoring data, although we note the observed occurrence of tritium in areas outside the calculated pathlines (for example, to the south of the disposal site) (Hartley et al. 2011a). We also note that the particle tracking used within the Connnectflow calculations are based on advection but not other relevant processes (for example, dispersion and diffusion), that may also influence contaminant migration. We welcome the use of techniques such as particle tracking to build confidence in numerical models, but expect LLW Repository Ltd to continue to make clear any limitations and areas of divergence from monitoring data.

A number of hydrogeological simulations were done in support of the 2011 ESC assessment calculations (Hartley et al. 2011a). The expected natural evolution and delayed coastal erosion scenarios[5] were used as the basis for the calculations, with steady-state simulations carried out at 2080 AD, 2180 AD, 2480 AD and 3180 AD.

Simulations that take into account the effects of spatial variability and a refined geological interpretation were also carried out for the expected natural evolution scenario, considered by the company to be the central scenario. A further simulation was carried out for the delayed coastal erosion/no erosion scenario at 7000 AD. Simulations considering early cap failure and the alternative model for the groundwater mound were carried out for the delayed coastal erosion/no erosion scenario. This use and development of multiple scenarios is considered good practice.

We consider that future ESC updates should seek to provide a clear linkage between the variant scenario models undertaken and the assessment scenarios utilised in the main ESC assessment. Where appropriate, full descriptions of the nature and implications of the variant scenario models should be presented (**Recommendation SUE22**).

The 2011 ESC has been able to conceptualise and model groundwater flow below and around the LLWR using a combination of site-derived and modelled sources. In line with the iterative approach to developing groundwater flow models, we expect future updates of the ESC to provide improvements to the understanding of groundwater flows.

[5] The expected natural evolution scenario assumes that coastal erosion of the facility begins at 3180 AD (that is 1000 years after the assumed date of closure of the facility). The delayed coastal erosion scenario assumes that the onset of coastal erosion of the facility is delayed until 5,000 years after the present date.

Environment Agency audit of the management of groundwater models

As noted in Section 2.2.4, in June 2013 we carried out an audit of the contractors that prepared the hydrogeological flow model and the groundwater pathway assessment model. The aim of the audit was to gain confidence that the calculations were completed under a suitable quality assurance regime and that relevant procedures were adhered to. We did not audit the appropriateness of the hydrogeological information for use in the models.

During our audit we confirmed that quality systems and procedures were in place for the main models used for contaminant transport (GoldSim, ConnectFlow and GRM[6]) that allowed the ongoing update of the site hydrogeology and geological models as and when information is generated (Fairhurst 2013). However, we note that the majority of the models and associated site information is managed by external contractors. We gained confidence that LLW Repository Ltd has appropriate in house hydrogeological expertise to act as an intelligent customer for the ongoing management and development of these models.

In Fairhurst (2013) we provided positive feedback on the groundwater modelling used to support the 2011 ESC. We identified a number of areas for improvement and made a number of recommendations to LLW Repository Ltd, including the development of a plan of audits to support work carried out since the submission of the 2011 ESC and the formalisation of a process to undertake audits and track actions arising from them (see Environment Agency 2015b). None of these related to issues that could impact the quality of the 2011 ESC. As part of our routine regulatory interactions we will monitor progress against the recommendations and actions raised in Fairhurst (2013).

In our review of safety case management (Environment Agency 2015b) we raised an FI with one objective of bringing safety case information and records 'in-house' thereby reducing reliance on contractor expertise (ESC-FI-022). Despite our audit not identifying any significant areas of concern during development of the ESC groundwater models, LLW Repository Ltd should continue to maintain its intelligent customer role and to make sure that it has access to all of its model data and input and output files.

LLW Repository Ltd used a number of different models and software packages in the 2011 ESC to model the characteristics and behaviour of groundwater. In the short and medium term these software packages and data sets will need to be maintained and managed to support the ESC. Over a longer period (corresponding with the period of authorisation) it is important LLW Repository Ltd is able to safeguard important geological input information in a format that would allow its utilisation in future software packages.

We concluded that the contractor organisations have well-established quality management systems that staff were aware of and actively used during the production of ESC materials (Fairhurst 2013). We also observed that significant effort had been dedicated to undertaking checks on the quality of input and output data.

Our audit confirmed that the hydrogeological information used in the assessment models had been subject to appropriate quality assurance.

Hydrogeological uncertainty

LLW Repository Ltd recognises that a key uncertainty in the hydrogeological modelling is the representation of parameter uncertainties in the properties of the glacial deposits of lithofacies B2 and B3. In the 3D geological models the key uncertainties relate to their spatial variability and the positions of the lithofacies boundaries.

The hydrogeological consequences of alternative conceptualisations were investigated in the 2011 hydrogeological model (Hartley et al. 2011a). Further analyses are also presented that explore the representation of the possible groundwater mound, the effects of spatial variability in the lithofacies

[6] Generalised Repository Model.

units and the use of the updated (September 2010) geological interpretation. These are variously referred to as variants and alternative concepts.

Hartley et al. (2011a) state that the objective of these analyses is to demonstrate that the ESC is robust to conceptual model uncertainty. However, it is not clear whether the objective was to explore specific areas of conceptual model uncertainty in the 2010 hydrogeological model (and underlying May 2010 geological model), or whether it was intended as a wider consideration of alternative conceptual models. Although we consider that the 2011 ESC demonstrates a good understanding of the main groundwater pathways, our interpretation is that the analyses are not as wide ranging as they could be to address alternatives to the 2010 hydrogeological model. For example, the implications of rapid transport pathways within unit B3 are not considered. We expect future updates of the ESC to further explore conceptual model uncertainty as well as realistic alternative conceptualisations (**Recommendation SUE23**).

Lithofacies unit B2 exhibits particular variability in lithology and associated hydrogeological properties. LLW Repository Ltd interprets this to be a consequence of the complex depositional environments under which it accumulated. Modelling studies were carried out to consider the effects of spatial variability in units B2 and B3 on groundwater flow by developing stochastic representations of hydraulic conductivity (Hartley et al. 2011a). In these studies a scale of 100 m was chosen on the basis that variability on this scale was considered likely to be significant. The investigation did not seek to link an effective length-scale and geomorphological form of sediment bodies to the scale used within hydrogeological models. As a result, it is not clear whether the company has developed a sufficient level of understanding of the geometry and geomorphological characteristics of features in units B2 and B3 that could significantly impact on groundwater conditions.

Notwithstanding the limitations noted above, consideration of the potential impacts of spatial variability on groundwater behaviour is welcomed. However, only 10 different realisations of spatial variability were considered and the geometry of particular sediment bodies is uncertain. It is therefore not clear whether the spatial variations in hydraulic conductivity have been sufficiently covered given the degree of confidence claimed in the modelling studies (Hartley et al. 2011a). We consider the investigations into sediment body variability are sufficient to gain an understanding of their behaviour on model outputs, but recommend that future updates of the ESC seek to better understand the nature and significance of geomorphology and the resulting depositional environment on spatial variability of hydraulic conductivity. Where appropriate the output of these investigations should inform the nature and number of groundwater flow model realisations (**Recommendation SUE24**).

We conclude that the hydrogeological models used in the 2011 ESC have appropriately identified and taken account of known uncertainties both in the model and the geological input information. We are assured that the iterative approach to hydrogeological modelling adopted by LLW Repository Ltd is capable of delivering ongoing improvements to site understanding. However, to assist in the delivery of ongoing improvements to management of uncertainty we recommend that in future updates of the hydrogeological modelling used to inform the ESC, LLW Repository Ltd should provide a more transparent and structured approach to the treatment of uncertainty in hydrogeological understanding (**Recommendation SUE25**).

The LLWR engineering design assumes that the construction of the perimeter cut-off wall and basal drainage material will be able maintain an unsaturated layer below all of the future vaults. This assumption is based on site characterisation and modelled information. However, it does not take account of observed site-specific variability in the height of groundwater, connectivity and hydraulic head. We consider that this aspect of the modelled LLWR performance represents an uncertainty with the potential to influence the near field behaviour of groundwater and the evolution of the LLWR engineering systems. Before the construction of future vaults we recommend that LLW Repository Ltd seek to better understand the nature of this uncertainty. As future vaults are developed we expect site-derived information to be used to inform hydrogeological modelling and the engineering design (**Recommendation SUE26**).

LLW Repository Ltd has used a combination of expert elicitation (Jackson et al. 2011) and detailed groundwater flow modelling to predict changes in groundwater levels and flow during and after the

period of authorisation. The 2011 ESC assessment approach is based on the expected natural evolution and delayed coastal evolution sequence (with some variant cases) developed in LLW Repository Ltd (2011c). We agree that these sequences are representative of potential site evolution sequences. By necessity, the predicted behaviour of groundwater height and direction of flow is based on a combination of current site characterisation information and modelled assessment. As the repository is developed, future updates of the ESC should seek to incorporate, where appropriate, further site-derived information together with further improvements in the functionality of the groundwater models. This might include, for example, changes in groundwater height associated with increased sea levels or changes in hydraulically effective rainfall (**Recommendation SUE27**).

LLW Repository Ltd uses the groundwater flow model to project the behaviour of groundwater adjacent to and below the LLWR engineering systems. Before excavation of the vaults and the exposure of the superficial geology we consider this approach appropriate. However, as vault construction progresses, we consider it important that the company should continue to work to gain an increased level of understanding of the adjacent superficial geology to better characterise the behaviour and response of adjacent groundwater as any future vaults are constructed. This might include the behaviour of groundwater adjacent to the LLWR and between the cut-off wall and disposals, as well as the behaviour of groundwater across the entire vault footprint. We would like to see the continued collection of hydrogeological information and material properties of the geologies adjacent to and below the future vaults. In particular, we would like to see ongoing characterisation and monitoring of the area covered by the final cap (**Recommendation SUE28**).

We note that the modelled hydrogeological sequence stops at the beginning of site disruption by coastal erosion. We expect the behaviour of leachate within the repository and the groundwater in and around the repository to change significantly as a result of the beginning of site disruption, for example as a result of erosion allowing rainfall to access the waste directly. We recognise that the nature and sequence of site disruption is highly uncertain, but consider that future updates of the ESC should seek to conceptualise and assess the potential impact of coastal erosion on the behaviour of leachate and groundwater within and adjacent to the eroding repository. We have raised a FI (ESC-FI-028) that addresses these issues.

Elsewhere in our review of the ESC, we have identified that the 2011 ESC relies heavily on modelled and elicited information, rather than site-derived data. In future updates of the ESC we would like to see a move towards increased use of site-derived information to supplement modelled and elicited data, wherever possible. This might include improvements to the environmental monitoring programme and recognition of this objective within ongoing site investigation programmes; with a view to adding to the modelled and elicited dataset[7] (see Recommendation SCM7 of Environment Agency 2015b).

The heterogeneous nature of the Quaternary deposits means that a high level of confidence in the spatial extent and layout of low and high permeability lithologies may not be achievable. In any hydrogeological assessment of these conditions, there will always be a level of uncertainty regarding the behaviour of groundwater at a small scale (10s to 100s of metres). Nevertheless, in terms of the 2011 ESC we consider that the geological interpretation and resultant modelling of the Quaternary geologies is appropriate.

In the expected natural evolution scenario LLW Repository Ltd assumes that there will be a 13% increase in rainfall (and hence hydraulically effective rainfall (HER) and recharge) due to climate evolution from 2080 (LLW Repository Ltd 2011c). According to Hartley et al. (2011a), substantiation for the increase in HER of 13% is provided by Thorne (2008). We reviewed Thorne (2008) and consider that the predicted HER increases associated with climate change are appropriate.

[7] In ESC-FI-029 we have requested the production of procedures for the review and update of elicited data used to inform the ESC.

The water budget is reviewed in Hartley et al. (2011a), but there is no discussion of uncertainties in HER or the proportions that form recharge or run-off. We recommend that LLW Repository Ltd further reviews its water budget and calculations of HER to assess uncertainties and changes over time and further substantiate the chosen parameter values (**Recommendation SUE29**).

As part of the wider site understanding forward programme we expect ongoing consideration of novel technologies and learning from other national and international projects to identify potential ways of improving site characterisation and to further reduce uncertainties. Given the current level of site understanding and conceptualisation of the geology and hydrogeology we do not expect further characterisation and reduction of uncertainties to significantly change the conceptualisation presented in the 2011 ESC. However, we do consider there is continued value in seeking improvements to existing site understanding, particularly where it can reduce key uncertainties identified by LLW Repository Ltd.

Overall, we conclude that LLW Repository Ltd has appropriately identified and investigated the main uncertainties associated with the geological and hydrological environment and taken account of them in the use of the model outputs in subsequent assessments. The company has carried out a systematic and comprehensive investigation programme into the geological and hydrogeological setting of the LLWR that has been able to reduce key geological and hydrogeological uncertainties in the 2011 ESC relative to previous assessments. This has allowed the development of a comprehensive and robust ESC.

However, LLW Repository Ltd has acknowledged that further investigations will be needed to continue to reduce key uncertainties and we have also identified this need in our review. We expect the company to develop a forward programme of work which includes tasks aimed at the continued reduction of uncertainties related to geology and hydrogeology and to work towards continuous improvement of conceptualisation and assessment (see ESC-FI-004).

2.2.4. Geochemical understanding

The 2002 PCSC included a dedicated geochemical interpretation report that described the nature of the geochemistry in and around the LLWR (BNFL 2002c). Since 2002, LLW Repository Ltd has carried out limited further investigations into geochemistry, while at the same time the conceptualisation of the hydrogeological environment has changed. Whilst we consider the geochemical understanding sufficient to inform the 2011 ESC, we would like to see the forward programme include further work to improve site understanding (**Recommendation SUE30**). This might, for example, include consideration of the implications of variability in the geochemical and mineralogical environment on contaminant sorption and further work to investigate retardation factors for the main contaminants that are appropriate to the latest understanding of site hydrogeology.

The 2011 ESC approach to the assessment of the impact of geochemical attenuation properties is realistic. Uncertainty in the use of solid/solution distribution coefficients (Kd values) to represent retardation is discussed in the features, events and processes (FEPs) and uncertainty tracking system (LLW Repository Ltd 2013a). LLW Repository Ltd states that Kd values are chosen 'in line with almost all assessments' and no alternative models are considered. We are content with the level of realism present in the geochemical parameters used in the geosphere models, but recommend that the forward programme includes further substantiation of Kd data, to demonstrate that the selected Kd data are consistent with site conditions, plus, review and incorporate as appropriate any future developments in the modelling of retardation (**Recommendation SUE31**).

2.2.5. Tritium

A plume of tritium (H-3) groundwater contamination, which arises from the trenches, is evident in both shallow and regional groundwater moving towards the coast (LLW Repository Ltd 2011a, d). Activity concentrations and the spatial extent of H-3 in the plume has decreased significantly since emplacement of an interim cap over the trenches and placement of a cut-off wall around the northern and eastern edge of the trenches in the 1990s (LLW Repository Ltd 2011d). The 2011 ESC includes an assessment of the distribution and behaviour of the H-3 plume to support understanding of the hydrogeology and contaminant flow.

LLW Repository Ltd has used the H-3 plume as a marker to assist in the validation of the groundwater models, for example the company notes that 'the calculated present day H-3 plume concentration of around 100 Bq l^{-1} is broadly consistent with the concentrations presently observed in groundwater close to the site' (LLW Repository Ltd 2011e). The company has also carried out further characterisation of the source term, together with an extensive ongoing monitoring programme specifically aimed at demonstrating the performance of the engineering improvements to the trench disposals (in response to Schedule 9 Requirement 7 of the current environmental permit[8]). In addition, the company has used monitoring data to estimate how much tritium has been lost from the trenches (Henderson 2011). This document did not form part of the 2011 ESC submission and was presented as part of ongoing regulatory reporting. We welcome the improved understanding of the tritium inventory provided by Henderson (2011) and consider that the nature and extent of the tritium disposals to the trenches has been appropriately investigated. The need to develop and maintain an understanding of the tritium source term should be included in any consideration of future trench monitoring infrastructure requirements (**Recommendation SUE32**).

The information presented in support of Schedule 9 Requirement 7 of the permit has demonstrated the effectiveness of the installation of both the cut-off wall to the north and east of the trenches and the interim trench cap in preventing tritium migration to the east, as well as reducing the extent of the western off-site tritium plume (BNFL 2007, Hunter-Smith 2011, LLW Repository Ltd 2008a, 2009a, 2010a, 2013b and Serco 2011a). We consider that LLW Repository Ltd should continue to collect tritium monitoring data, with the specific objective of demonstrating the effectiveness of the existing trench cap and cut-off wall and the extent of the existing off-site plume (see Section 2.4.12).

The 2011 ESC effectively used environmental monitoring information in the development of understanding of the groundwater pathway. While we understand that the tritium distribution cannot be used directly in the hydrogeological models, we encourage LLW Repository Ltd to continue to use the empirical tritium data to inform the ongoing hydrogeological conceptualisation and modelling, for example, improving understanding of groundwater flow paths and velocities.

While we accept that the human health consequences of the tritium plume are low (LLW Repository Ltd 2011b, e), we expect LLW Repository Ltd to continue to monitor the offsite tritium plume to maintain an understanding of the release and to assist in further understanding of site hydrogeology (see Section 2.4.12 and ESC-FI-002).

2.2.6. Extended disposal area

LLW Repository Ltd has presented a separate assessment of the Extended Disposal Area (EDA) comprising 6 further vaults (Vaults 15 to 20) to the immediate south-east of the Reference Disposal Area (RDA), lying adjacent to Vault 14 and the southern end of the trenches (LLW Repository Ltd 2011g). The area proposed for the EDA is geologically and hydrogeologically similar to the RDA. The bases of the EDA vaults would be excavated into unit B2 and would be approximately 4 m above the regional groundwater level (LLW Repository Ltd 2011g).

We note that the depth of groundwater below the footprint of the EDA is shallower than for the RDA. Thus, uncertainty associated with the extent of the unsaturated zone may be more significant in determining the likelihood and nature of overtopping occurring. To reduce this uncertainty, we will expect an increased level of site characterisation in the future to support hydrogeological assessments of the EDA (**Recommendation SUE33**).

As with the development of all new vaults we will expect that, before the development of the EDA vaults, LLW Repository Ltd updates the hydrogeological and geological model using all available site-derived information.

[8] Schedule 9 Requirement 7 requires LLW Repository Ltd to establish a comprehensive programme of monitoring to confirm the integrity of both the interim cap covering past disposals and the bentonite cut-off wall constructed to the north and east end of the disposal area. An annual report shall be provided to us of the output from that monitoring programme.

At present the EDA assessment is presented separately to the RDA assessment. We expect an integrated assessment to be presented as part of the next major update to the ESC (see ESC-FI-011). This should include the integration of the hydrogeological and geological models for the EDA and RDA.

Given the similarity between the conceptual and computer models for the geology and hydrogeology of the EDA and the RDA, our comments on the RDA as outlined in the previous sections are also of relevance to the EDA. We have no further comments specific to the EDA.

2.3. Site evolution

The 2002 PCSC first considered the potential for the LLWR to be destroyed by coastal erosion. At that time, coastal erosion was 1 of 3 potential 'termination events' considered that might result in the destruction of the LLWR (the other 2 being valley glaciation and regional glaciation). Our review of the 2002 PCSC concluded that it failed to make an adequate or robust argument for continued disposals of LLW because, amongst other things, the LLWR is likely to be destroyed by erosion in 500 to 5000 years and will (according to BNFL's assessments) result in conditional risks of up to around 10^{-4} per year (Environment Agency 2005), which are significantly in excess of our risk guidance level of 10^{-6} per year. Since 2005, LLW Repository Ltd has made significant progress in better understanding the timing and nature of coastal erosion, the resulting disruption of the LLWR and the implications of this for environmental safety. Using this improved understanding, the company updated its coastal erosion assessment model. The use of a better underpinned assessment model together with improved understanding of the inventory gained since 2002 resulted in coastal erosion impacts that are below the risk guidance level in the 2011 ESC (LLW Repository Ltd 2011b).

To address some of the necessary improvements to the 2002 PCSC, we included a requirement in the 2006 LLWR authorisation (Schedule 9 Requirement 2) that stated that the operator, by 1 May 2008, must 'provide the Agency with a full report of a comprehensive review of national and international developments in best practice for minimising the impacts from all waste disposals on the site. This shall include a comprehensive review of options for reducing the peak risks from deposits of solid waste on the site, where those risks arise from potential site termination events (for example coastal erosion and glaciation) and potential future human action.' LLW Repository Ltd's response to Requirement 2 concluded that the facility is highly likely to be destroyed by coastal erosion within a few 1000 years (LLW Repository Ltd 2008b).

Since the submission of the Schedule 9 Requirement 2 response, LLW Repository Ltd has continued to undertake a wide ranging investigation programme using a range of subject matter experts, for which it has actively sought peer review. The 2011 ESC is the first time that all of the studies and supporting information used to characterise the coastal evolution sequence have been presented as a single case. The Level 2 Site Evolution document (LLW Repository Ltd 2011c) summarises the outcome of this substantial work programme.

As a result of this programme, LLW Repository Ltd concluded that it is near-certain that the LLWR will be disrupted by coastal erosion, commencing within a few 100 to a few 1000 years from now. This conclusion is based on the following factors:

- proximity of the LLWR to the coast
- current rates of erosion locally
- the understanding that the rate of erosion is related to the rate of sea level rise
- the forecast rise in global sea level based on global climate studies

LLW Repository Ltd sought to characterise the timing and nature of coastal erosion and the resulting disruption of the LLWR in the 2011 ESC (LLW Repository Ltd 2011c). Because of the near certainty of coastal erosion causing disruption of the LLWR at some point in time, other long-term site disruption mechanisms such as glaciation and denudation, which played a significant role in the 2002 PCSC, are not assessed as significant possibilities in the 2011 ESC. Given the evidence presented, we consider this reasonable. In our review, we have considered whether LLW Repository Ltd's assessment of site evolution has used sound science, together with an understanding of relevant natural systems at all scales.

Given the importance of coastal erosion in the development of the 2011 ESC, we sought to gain confidence that LLW Repository Ltd's investigation, review and assessment of coastal erosion was robust and supported by the best available scientific and engineering understanding in the fields of climate change and coastal processes. Since 2006 we have liaised extensively with the company to ensure this. We expected the understanding of the coastal erosion sequence and causal factors to be developed from a wide range of sources at different spatial and temporal scales. We were satisfied that this was the case.

Our review here builds on our previous review of site understanding in the Schedule 9 Requirement 2 submission (Environment Agency 2009b). Where appropriate, Environment Agency coastal process scientists, climate change scientists and geomorphologists assisted in our review.

Our review focused on the following aspects of the 2011 ESC site evolution report:

- the use of climate change science in the development and conceptualisation of the erosion sequence
- the characterisation of the west Cumbrian coastal environment
- the understanding of the response of the Drigg shoreline to climate change
- the interaction of the eroding coastline with the LLWR
- the development of coastal evolution scenarios for use in exposure assessments
- the identification and treatment of uncertainty
- the use of appropriate supporting information, such as outputs from international climate change studies

Due to the level of certainty associated with coastal erosion occurring at some point in time, we required the scope of the coastal erosion investigation programme to be appropriate for a normal or expected evolution scenario for the LLWR. This differs from the 2002 PCSC as well as most other near-surface repositories, where site disruption (including coastal erosion) is typically considered as a 'what-if' scenario. To meet the requirements of the GRA, we expect a robust, thoroughly underpinned assessment of coastal erosion that takes full account of the information available and the associated uncertainties.

The GRA requirements make it clear that the operator must demonstrate passive safety for the period after authorisation has ended. Therefore, LLW Repository Ltd has assumed that no future human action will be taken to protect the LLWR from natural evolution such as coastal erosion after the period of authorisation. Also, that any engineered coastal defences constructed during the period of authorisation will not survive long enough to provide any meaningful long-term protection. Long term safety arguments for the 2011 ESC ultimately centre on the overall acceptability of disposal itself, given the potential radiological implications of disruption.

None of this precludes the possibility that future actions will be taken to protect the LLWR. We will expect the company to make efforts to ensure that awareness of the site and any risks associated with it continues during and after the period of authorisation, to inform future communities and facilitate future action should that be deemed necessary against future standards and expectations.

One objective of the 2011 ESC site evolution investigations was to develop a sufficient understanding of coastal erosion to define an 'expected' coastal erosion scenario, along with variant scenarios to encompass the range of uncertainty for use in the safety assessment (LLW Repository Ltd 2011c). We examined the supporting investigations, treatment of uncertainty and their subsequent use in the development of scenarios.

2.3.1. Climate evolution and sea level change

The main influence on the rate of evolution of the Drigg coast will be climate change, its implications for sea level rise and subsequent coastal erosion and changes to current landscape and coastal processes. LLW Repository Ltd has carried out an extensive programme of research and investigation into projections of future climate and sea level change, drawing from relevant national and international studies.

LLW Repository Ltd uses short-term climate change projections from the 2007 Intergovernmental Panel on Climate Change (IPCC) fourth assessment report in the 2011 ESC (IPPC 2007). Global sea level is expected to rise by 0.2 to 0.8 m over the 21st century. Taking into account isostatic rebound, this equates to a rise of 0.1 to 0.74 m by 2100 AD at the Drigg coast (Thorne 2009). The 2007 IPCC also predicts global temperatures will rise by 1.1 to 6.4°C over the same period.

There has been significant international effort since 2007 to better understand the impacts of global scale climate changes. Of particular relevance were concerns that the IPCC fourth assessment report did not describe the full range of sea level rise scenarios that could happen during this century. This issue is addressed in the 2009 UK Climate Projections (UKCP09) (Jenkins et al. 2009) by providing users with estimates of sea level rise and surge increase beyond the likely range but within physical plausibility. These upper end (H++)[9] projections attempted to quantify how acceleration in the melting of the Greenland and Antarctic ice sheets could contribute to global change. The H++ projections gave increases of mean sea level of between 0.93 to 1.9 m by the end of this century, with changes to storm surge potentially raising this further. We would have expected that LLW Repository Ltd would have used these data in assessment of the effects of sea level change on the LLWR.

The estimates of sea level rise to 2100 used in the 2011 ESC are in line with the central estimates of sea level rise predicted in UKCP09. However, by not taking into account the H++ projections, the 2011 ESC does not reflect the full range of sea level increase that may happen up to 2100. LLW Repository Ltd has not carried out explicit modelling to illustrate what a greater change to mean sea levels might mean for erosion at the site up to 2100. An assessment that covers the National Planning Policy Framework (Department for Communities and Local Government 2012) Planning Policy Statement 25 (Her Majesty's Stationary Office 2010) allowances is provided, but this is based on science that is now over 10 years old. Although assessment of more extreme, but physically plausible scenarios (such as H++) would be beneficial, we do not consider it necessary at this stage as they are extremes and are suitably bounded by the longer-term projections considered by LLW Repository Ltd over a 1000 and more years (discussed further below). We do not consider that they would influence the outcome of the assessment of coastal erosion or our review. However, for completeness, we recommend that the company improves the ESC further in future by consideration of these more extreme but physically plausible scenarios, such as the H++ scenario, to identify the full range of potential sea level increases and implications on the nature and timing of the predicted erosion sequence (**Recommendation SUE34**).

LLW Repository Ltd's projections of sea level rise over longer timescales used in the 2011 ESC are based on the output of the international BIOCLIM project (BIOCLIM 2004). Over the next 1000 years, global sea level is expected to increase by between 1.7 to 21.7 m, and between 9.1 to 26.4 m over a few thousand years. For the Drigg coast, the company estimates a relative sea level rise of between 6.5 to 23.8 m, with a best estimate of 14.9 m on a timescale of a few thousand years (Thorne 2009). These values take into account local isostatic uplift, plus the effects of thermal expansion of the oceans, loss of ice caps and valley glaciers and partial to complete loss of the Greenland and West Antarctic ice sheets.

LLW Repository Ltd does not consider it appropriate to assign probabilities to individual cases of climate and sea level change; rather ranges are quoted that are indicative of a range of climatic conditions. We agree with this approach.

The nature of sea level rise projections means that they will always have a high level of uncertainty. To take account of the wide range of sea level change predictions, the 2011 ESC assessed the effect of bounding high and low sea level increases on the evolution of the coastline. Again, we consider this approach to be appropriate.

---

[9] The High-plus-plus (H++) scenario represents a wider range of relative mean sea level rise and storm surge changes. The H++ range is not intended to replace the likely range of sea level rise and future surges, but rather it provides users with estimates of sea level rise and surge increase beyond the likely range but within physical plausibility. It is useful for contingency planning when a higher level of protection might be needed.

We recognise that climate science is rapidly evolving with future predictions changing and do not expect the ESC to be updated to reflect all changes to climate science understanding; instead we expect climate change forecasts to be reviewed as part of major ESC reviews.

Over the period of authorisation, LLW Repository Ltd has committed to maintain a watching brief on 'development of climate scenarios in relation to repository safety assessments or other long-term considerations' (LLW Repository Ltd 2013c). In between major ESC reviews, we recommend that the company maintains a good understanding of the latest developments in climate change science, for example the results of the fifth assessment of the IPCC (IPCC 2013) and its potential impact on the ESC projections (**Recommendation SUE35**).

We note that, with the exception of the International Atomic Energy Agency (IAEA) Modelling and Data for Radiological Impact Assessments (MODARIA) project (IAEA 2014), there is limited scientific research investigating the effects of climate and sea level change at times greater than about 100 years in the future. Longer-term climate change investigations carried out to support radioactive waste disposal ESCs are often focused on deep repositories. As part of the forward programme, we recommend that LLW Repository Ltd keeps up to date with research on short-term and long-term climate change projections (**Recommendation SUE36**).

Over the period of authorisation, the repository will be subject to ongoing isostatic[10] changes that will result in localised changes in relative sea level. Over the whole life of the LLWR isostatic movement could influence the magnitude of sea level change. The LLWR is located on an axis point between rising isostatic levels to the north and falling isostatic levels to the south. While not significantly influencing the timing and nature of site disruption, we considered that the local quantification of isostatic changes could improve the understanding of the impact and significance of sea level rise.

Therefore, we asked LLW Repository Ltd to carry out an assessment of the viability, usefulness and practicality of taking site-derived isostasy measurements of relative ground height over an extended timeframe (ESC-TQ-SUE-010). Following review of the evidence provided in response to our IRF (Baker 2013) we accept that the uncertainty associated with the measurement of local isostasy is minor compared with the predicted range of sea level change and would therefore have minimal influence on the assessment and overall ESC. We therefore agree with the company's opinion that no further benefit would be provided by the onsite measurement of isostatic uplift and that their assessment has appropriately taken account of the impact of isostatic uplift on the magnitude of local sea level change. This situation may change as sea level change predictions, modelling and survey techniques are improved. We therefore recommend that LLW Repository Ltd should re-visit this issue as part of future ESC reviews (**Recommendation SUE37**).

Storm surge events can result in temporarily greater water depths that can bring about rapid and potentially significant changes in the shoreline environment. Storminess is taken into consideration in the 2011 ESC, based on past events that have impacted the west coast of Cumbria. As discussed by Royal Haskoning (2010), no evidence is presented in UKCP09 for an increase in tidal range or storm surge during this century. However, if the nature and magnitude of storms were predicted to change over longer timescales, then we would expect future updates of the ESC site evolution assessment to take this into account. LLW Repository Ltd should maintain a watching brief on the development of understanding long-term changes in storminess associated with climate change, as well as the frequency and magnitude of storm surge events (**Recommendation SUE38**).

The topography and layout of the LLWR means that reference sea level changes and coastal recession predictions suggest that the vaults are likely to be undercut by the sea, whereas the most easterly trenches may be directly eroded or inundated by the sea. The physical effect of inundation on the repository is likely to be significantly different from undercutting or direct erosion. The nature and safety implications of inundation of all or parts of the repository has not been

[10] Isostasy is the vertical movement of the earth’s upper crust in response to the removal of Quaternary ice sheets.

addressed in performance calculations within the ESC and we therefore recommend that it is considered further in future assessments in our FI ESC-FI-028.

Overall, we are satisfied that LLW Repository Ltd has appropriately taken account of evidence available on climate evolution and likely sea level change, along with wider factors that may influence this.

2.3.2. Coastal studies programme

The main influences on the nature and form of coastal landscape evolution in the vicinity of the LLWR are:

- anthropogenic factors such as climate change policy, land use and coastal engineering
- the magnitude and rate of sea level rise
- the near-shore wave regime and related regional and local sediment transport processes, in particular interactions with the beaches and other coastline features in the vicinity of the LLWR
- the nature and composition of the materials likely to be eroded
- the implications of all the above for cliff recession rates

These issues are considered as part of LLW Repository Ltd's coastal studies programme and their influence on the LLWR assessed (LLW Repository Ltd 2011c). The coastal studies programme sought to describe the geometry of the erosion sequence, the sediment transport processes and the resulting coastal landform. The investigation used a combination of monitoring and site investigations to understand and characterise the local coastal environment and its evolution. The programme has appropriately conceptualised the coastal landscape, marine processes and meteorological conditions around the LLWR. A good understanding of the nature and form of coastal landscape evolution and the causal mechanisms is essential to inform coastal recession modelling and the conceptualisation of the LLWR erosion sequence. We consider that the 2011 ESC has demonstrated a good understanding of these issues.

The coastal studies were informed by extensive geophysics studies (Halcrow 2010a), together with existing site investigation information. The response to sea level change and the nature of coastal erosion will be partly determined by the geology and particle size distribution of the affected geologies. It is therefore important that the properties of the superficial sediments located between the current coastline and the LLWR are understood. Due to their importance in determining the rate of erosion and the potential benefits from the use of more site-specific coastal recession models, we recommend that local shallow geological information continues to be collected from ongoing site development activities, cliff exposures and, if required, dedicated investigation programmes (**Recommendation SUE39**).

The 2011 ESC sought to align coastal recession models with the outputs of site investigations and geophysical surveys. Because of the importance of particle size distribution in determining the nature and rate of recession, we recommend that future updates of the ESC consider the potential for increased use of information on local shallow geological sequences in the development of site-specific coastal recession models (**Recommendation SUE40**).

The impact of the known heterogeneity in the Quaternary geology on the form of the erosion front has been considered by LLW Repository Ltd. The company states that geological heterogeneity may result in the formation of localised headlands and bays. This may mean 'some limited part of the repository might be disrupted (most likely by undercutting) sometime in advance of the erosion along the full frontage of the repository. In the case of rapid sea level rise and erosion, this can only be a few decades in advance, since the whole repository is eroded out in a matter of centuries. In the case of slow sea level rise and erosion, this might be about a century in advance, given the whole repository is eroded over millennia' (LLW Repository Ltd 2011c). We are confident that these changes and variations in erosion form are adequately accommodated in the large range of uncertainty identified in the timing of the beginning of site disruption and that they do not significantly change the predicted earliest beginning of erosion. However, while we accept that these variations in the commencement of the disruption of the LLWR are appropriately accommodated within the 2011 ESC, we consider that there is scope for improvement in the manner of their presentation. We recommend that LLW Repository Ltd considers how differences

in localised erosion rates resulting from geological heterogeneity and complex coastal geomorphological processes could be better communicated and presented within future updates to the ESC (**Recommendation SUE41**).

We queried how the role and significance of the dune system had been considered in the assessment of the evolution of the coastline (ESC-TQ-SUE-022). In addition to informing our review of the 2011 ESC, this TQ sought information on the long-term behaviour of the dune system to inform our Habitats Regulations Appropriate Assessment (Environment Agency 2014a). In response, LLW Repository Ltd provided clarification of the significance of the dune system during coastal erosion (Halcrow 2012).

LLW Repository Ltd has demonstrated that the Drigg Dunes (located between the LLWR and the coast and along the Drigg Spit) are not expected to play a significant role in determining the rate and direction of coastal erosion. Over the entire repository erosion sequence we agree with this interpretation. Over shorter timescales, because of the complex nature of dune generation and maintenance processes, together with uncertainty associated with the response of the dunes systems to coastal erosion and climate change, we consider it is important that the ongoing viability and health of the Drigg dune system is regularly monitored as part of the coastal monitoring programme to determine the role of the dunes in the wider coastal system (see ESC-FI-019).

In ESC-TQ-SUE-019 we raised a number of questions seeking clarification on how the assessment of the coastal evolution sequence prediction took account of extreme events. We asked LLW Repository Ltd to confirm how extreme events had been accommodated in the assessment, and to demonstrate that extreme events would not result in changes to the presented coastal evolution sequence. In response, LLW Repository Ltd confirmed that the effects of extreme events had not been superimposed onto the projections of future coastal change in the 2011 ESC (Halcrow 2013a). Rather, the effect of storm events is included within the models of coastal recession, which are based on decade long coastal recession histories, including storm events. The resulting models assume a linear regression of the coast that smoothes out the effect of single, more extreme events that could occur over extended timeframes, so as to take account of this complexity within the 2011 ESC. We consider that this approach is appropriate for gaining an understanding of the nature and timing of the beginning of LLWR disruption and given the long timescales predicted before coastal erosion of the LLWR begins, adequately takes account of more extreme events that could periodically occur.

Future extreme events will none the less have a role in determining the long-term coastal erosion rate near the LLWR. However, the resulting change to the projected erosion rate will be small when compared to the very high range of uncertainty and the extended time frame over which, erosion will happen. As erosion of the Drigg coastline progresses it should be possible to characterise the response of the coast to extreme events. We would expect the ongoing coastal monitoring programme requested in ESC-FI-019 to identify the need for surveys after significant storm events with the specific objective of investigating the nature and extent of the coastal response to extreme events. Although we accept that over the long-term storm events will not have a significant impact on the overall predicted coastal erosion rate, these events could become more important as the coast approaches and encounters the LLWR in the future. We recommend that LLW Repository Ltd considers investigating these phenomena further or identifying any national or international studies that support further understanding (**Recommendation SUE42**). We conclude that the impact of extreme events on the form and beginning of LLWR disruption are appropriately accommodated in the presented 2011 ESC assessments.

A sudden change of the River Irt's path (known as avulsion) may have happened in the past with the River Irt previously directly discharging to the Irish Sea through the current Drigg Point. However, the evidence is equivocal and of limited extent. LLW Repository Ltd considers that the balance of evidence is that no such change has occurred in the past. Rather, the previous course of the River Irt (ca. 10,000 years BP) was SSE from Holmrook to join the present day River Mite just upstream of the present-day A595 crossing of the Mite, then SW to the sea entering at or very near the present day tidal channel of the estuary. The company consider that this view is firmly supported by surface geological mapping and present day topography. In ESC-TQ-SUE-022 we asked LLW Repository Ltd if the 2011 ESC had considered future avulsion of the River Irt as a

potential evolution mechanism that could either result in an increased rate of LLWR erosion or a change to the predicted form of erosion (for example, mechanism or direction). The company concluded that there was no unequivocal evidence that a river channel has ever penetrated through the Drigg spit/promontory, but even if avulsion of the River Irt were to happen in the future, it would not affect the predicted timing or form of erosion of the disposal area, as this is determined by erosion of the coastal frontage (Halcrow 2012). We agree with this conclusion.

An important outcome of LLW Repository Ltd's coastal studies programme is the conclusion that, even if there is no change to current sea level, erosion of the LLWR will happen, albeit over a longer time frame (LLW Repository Ltd 2011c). This is because the LLWR is located in an evolving and dynamic coastal environment that is subject to erosive forces from the coastal, fluvial and estuarine environment. We agree that the LLWR is almost certain to be subject to coastal erosion over the next few thousand years, even if climate change predictions are incorrect or climate change mitigation measures are effective in preventing sea level rise. We also note that the predicted beginning of site disruption described in the 'no sea level rise scenario' is expected to happen before the LLWR is disrupted by other natural erosion mechanisms, such as glaciation and denudation. Therefore, we agree with LLW Repository Ltd's approach of assessing disruption of the LLWR by coastal erosion as the expected evolution scenario.

2.3.3. Future coastal evolution

Forecasting the development of the Cumbrian coastline in the vicinity of the LLWR must take into account the interaction of a number of important influences which have uncertainties associated with them. The influences include local sediment sources and transport, beach volume change and its implications for the degree of ‘natural’ protection afforded by the beach at the cliff toe. To understand the response of the coastline in the vicinity of the LLWR to coastal erosion, LLW Repository Ltd commissioned a number of coastal evolution modelling studies. As required by the GRA, the 2011 ESC does not take into account potential future human actions after the period of authorisation, both associated with the LLWR or otherwise, that could influence the behaviour of the coastline in the vicinity of the LLWR (for example the construction of coastal defences).

Two separate modelling approaches were used to inform projections of coastal recession in the vicinity of the LLWR. Firstly, empirical cliff recession modelling was carried out, that simulates the feedback between cliff recession, coarse sediment supply and growth of the gravel storm beach at the cliff foot (Fish et al. 2010). Secondly, Royal Haskoning's Soft Cliff And Platform Erosion (SCAPE) process-based model was used to provide an alternative estimate of cliff recession (Royal Haskoning 2010). Although the SCAPE model was developed to model the erosion of soft cliffs on the north-east coast of England, we consider it acceptable for use in the Drigg coastal environment. A model was also set up to predict the evolution of the Irt Estuary, providing an indication of the estuarine geomorphology at specified time intervals, as opposed to predicting the process of change (Fish et al. 2010).

The coastal change models are based on bounding high and low sea level rise scenarios, based on sea level rises of 1.1 m to 21.1 m at 1000 years after present (AP) and 7.3 m to 24.6 m at 3000 years AP. Although the models were run over similar assessment periods, there are a number of differences in underpinning information supporting them. For example, the empirical model is based on the climate change projections outlined by Thorne (2009) that are based on BIOCLIM. However, the SCAPE model used UKCP09 medium and high emission scenarios to inform changes up to 2100 (Jenkins et al. 2009) and Thorne's (2009) projections thereafter.

The outputs of these models were reasonably consistent (Fish et al. 2010), providing reassurance in the appropriateness of the modelling approach. The empirical model projected that the eroding coastline will reach the site boundary within 500 to 800 years AP (low sea level rise scenario) or within 400 to 600 years AP (high sea level rise scenario). This model predicted loss of the entire repository by 1500 to 1900 years AP. The SCAPE model provided a lower estimate of the eroding coastline reaching the site boundary between 300 to 400 years AP and an upper estimate of 800 to 900 years AP. The high sea level scenario would be considered a worst-case scenario for sea level change. Estimates for loss of the whole LLWR vary from 1500 to 1900 years AP.

The supply of sediment from outside of the assessment area is acknowledged as an important uncertainty determining the nature and extent of erosion. Royal Haskoning (2010) makes no

reference to the estimates of future sediment supply based on the outputs of the geophysical surveys of the site frontage and Drigg barrier, carried out in autumn 2009 (Halcrow 2010a). We recommend that future updates to the cliff recession models incorporate the outputs of these geophysical studies and the derived clast size distribution sections (**Recommendation SUE43**).

There are limited data available for similar coastal settings for comparison purposes. However, the estimates presented in the 2011 ESC for the time at which erosion of the LLWR begins, fall within estimates extrapolated from the Environment Agency's National Coastal Erosion Mapping (NCERM) project.

LLW Repository Ltd considers that the presented numerical model predictions of coastal recession given in the 2011 ESC overestimate the rate of erosion that could be sustained over the long-term (LLW Repository Ltd 2011c). We agree with this conclusion, although due to the extent of uncertainty associated with the response of the coastal landscape to sea level rise we consider the predicted rates to provide an appropriate conservative basis for subsequent radiological assessment.

We consider the models used by the company and the references cited, to be robust and appropriately applied for the coastal erosion sequence up to site disruption.

The basis of the selection of 1000 years AP as a reference scenario, and whether it was considered representative or realistic, was unclear within the 2011 ESC. Because of the importance of the 1000 year reference case in the 2011 ESC assessments, we queried its selection as 'appropriate as a reference time for coastal recession to reach the disposal area site boundary (for example for the onset of erosion of the disposal facility)*'* in ESC-TQ-SUE-025*.* We sought clarification of the term 'appropriate', given LLW Repository Ltd's model outputs suggest a potential for beginning earlier. In response, Sumerling (2012) stated that uncertainties in data and modelling and assessment considerations and judgements were the 2 main factors that led to the selection of the1000 year reference period. The chosen 1000 year period was both representative of the uncertainties in the timing of the commencement of repository erosion and source term hazard reduction seen after the end of the period of authorisation. Given the large uncertainties in the timing of the beginning of erosion of the repository, the 2011 ESC has used values that spanned the credible range, with the 1000 year reference case located appropriately within the credible range. Although we agree with this approach in the development of a reference scenario, it is not stated in the 2011 ESC and its inclusion would have better informed our review of the subsequent assessment, as well as clarifying the role of expert judgement in the development of the 2011 ESC. We would expect the expert judgements used to inform the reference scenario to be subject to review in future updates of the ESC.

Halcrow (2012) and LLW Repository Ltd (2011c) present an annotated figure showing the hypothetical future arrangement of the coastal landscape adjacent to and south of the LLWR. This hypothetical coastal arrangement presents a scenario that in general terms assumes a consistent, linear retreat of the present day coastline. This approach is reasonable given that it follows current best understanding. However, the possibility of different long-term outcomes should be considered to the extent technology and understanding allows, as threshold tipping events may trigger unforeseeable step-changes in coastal processes. In reality coastal erosion processes will exploit weaker geologies and existing coastal features, especially after storm events. At the LLWR, it is likely that the top of the Sherwood sandstone and the presence, or absence, of sand based superficial materials will influence the coastline. This may result in the beginning of localised erosion of small areas of the LLWR before the earliest onset predicted in the models. We accept that the best available models and supporting information, are not currently capable of predicting any such localised erosion. Current models 'smooth out' such potential localised erosion events over the long timescales involved. We also accept that this issue is unlikely to have a significant impact on overall predictions of erosion timescales, which are also suitably cautious and will not influence the outcome of the 2011 ESC assessment. However, as the ESC is developed in the future, we will expect LLW Repository Ltd to make use of improving understanding and evidence associated with coastal erosion more generally and also specific to the Drigg coastline.

2.3.4. Delayed coastal erosion/no erosion scenario

In our review of LLW Repository Ltd's 2008 Schedule 9 Requirement 2 submission we recommended that the 2011 ESC include proportionate consideration of the impacts that could arise in the very long-term if the facility were, for some unforeseen reason, not to erode (Environment Agency 2009b). This recommendation was based on the output of the 2002 PCSC that had indicated some assessed risks several tens of thousands of years after closure that were significantly higher than those in the first 10,000 years, due to ingrowth of uranium -234 (U-234) daughters and the possible discharge of radionuclides in groundwater to a terrestrial biosphere following a significant decrease in sea level associated with glaciation.

The 2011 ESC included a delayed coastal erosion scenario, in which impacts up to 10,000 years after present are considered. We did not consider that this scenario covered a long enough period of time. We therefore raised ESC-RI-ASO-006 which asked LLW Repository Ltd to provide a further evaluation of how the site might not be eroded within a few 1000 years, together with an assessment based on assuming that the site continues to exist up to 250,000 years after the present.

In response, LLW Repository Ltd presented a scenario in that, due to a fall in sea level within about 10,000 years, the LLWR is not subject to coastal erosion (LLW Repository Ltd 2012b). The fall in sea level is hypothesised as being due to rapid cessation and control of global CO_2 emissions and of reduction in CO_2 levels in the atmosphere, leading to reversion towards a climate evolution near to the natural scenario, in the absence of greenhouse gas emissions.

This scenario is identified by LLW Repository Ltd to have a very low probability of happening, but we consider that it cannot be ruled out because of the high level of uncertainty associated with very long-term climate change and site evolution. The only credible scenario in which the LLWR may escape coastal erosion is if the sea level does not rise significantly and begins to fall within a few thousand years. This situation is only expected to happen as a result of the reduction in global temperatures, contrary to current climate change predictions (for example IPPC 2007).

This scenario will have a lower probability than the maintenance of current sea levels in the delayed coastal erosion scenario described in the 2011 ESC. Associated with the delayed coastal erosion scenario, it is predicted that if current sea levels are maintained, a local rate of coastal erosion estimated at about 0.2 m per year will happen. If this erosion rate remained constant, then the start of LLWR erosion could be expected to happen in a period from around 2,500 to 5,000 years AP.

Based on the evidence we accept that there is a very low probability that the LLWR will not be disrupted by coastal erosion within a few 1000 years and that a scenario involving the LLWR remaining undisturbed for 10s or 100s of 1000s of years is extremely unlikely. However, this cannot be totally ruled out and we discuss the implications of this in Environment Agency (2015e).

2.3.5. Erosion of the repository waste mass

Within the 2011 ESC, LLW Repository Ltd describe the timing and process of erosion of the waste mass when erosion of the repository commences. The waste mass erosion mechanisms and rates are important as they directly inform the long-term radiological assessments. The erosion mechanism will be influenced by the relative height of the shoreline and the geotechnical properties of the eroding waste mass, surrounding engineering and underlying natural sediments.

The 2011 ESC presents simple conceptual models and modified process based models used to predict the waste erosion sequence. The sea level models indicate that sea level is likely to be lower than the base of the vaults (14 m AOD) when cliff recession impinges on the LLWR (Fish et al. 2010). For the high sea-level rise scenario, erosion below the base of the vaults is less likely to happen, with increased likelihood in the 1000 year reference scenario. While we consider that this prediction is valid and sufficient to support the 2011 ESC assessments, the actual erosion sequence and interaction between the coastline and the vaults is likely to be more complex and differ along the length of the facility.

Because of the predicted long period of erosion and the uncertainty around its nature and direction, it is reasonable to assume that a number of shoreline profiles may exist at any one time, with the erosion profile changing along the shoreline frontage. LLW Repository Ltd has sought to

identify a full range of possible shoreline frontages in order to inform the subsequent radiological assessment.

LLW Repository Ltd differentiates between the behaviour of the containerised waste in the vaults and the loose tipped waste in the trenches during the erosion process. The nature of the erosion front is likely to be different for the trenches and for the vaults. This may result in different waste exposure mechanisms and differing mechanisms of exposure to future beach users. As the LLWR erodes, the erosion front will vary, reflecting its layout, the heterogeneity of the waste and the direction of erosion. The visual appearance of the eroding waste may vary from adjacent natural Quaternary materials, with the shape and appearance of the beach cliffs potentially being dominated by the presence of waste.

During our initial review of the 2011 ESC we considered that the description and conceptualisation of the LLWR waste and engineering material erosion sequence may not have been adequate to describe its likely complex and variable nature. This could mean that the subsequent assessment of radiological impacts may not be sufficiently comprehensive, consequently we required further information in ESC-TQ-SUE-011. We sought an improved description of the geotechnical properties of the waste and LLWR engineering systems and how they may influence coastal erosion and the stability of the eroding waste mass. In response, LLW Repository Ltd held a workshop aimed at improving understanding of the stability of the eroding waste mass and the implications on radiological impacts (Garrard et al 2012). As discussed further in Environment Agency (2015d), we consider that this work has resulted in a greatly improved geotechnical understanding of waste erosion. LLW Repository Ltd has developed more realistic coastal profiles that will assist in the communication and assessment of site evolution within the ESC.

We consider that the 2011 ESC and subsequent work has resulted in a conceptualisation that suitably informs the assessment of the LLWR erosion sequence, one that takes into account all reasonable interactions between the repository and the eroding coastline using sea level predictions and conceptualisation of the erosion sequence. Work subsequent to the 2011 ESC has provided an improvement in understanding of the waste erosion sequence and better reflects the nature of coastal erosion. However, we consider that the understanding of the LLWR erosion sequence would benefit from further investigation and conceptualisation, to better inform future radiological assessments and reduce uncertainties further. We would like future updates of the ESC to be informed by further investigations into the behaviour and response of the coastal system to the erosion of the waste mass. We request this further work in ESC-FI-028.

LLW Repository Ltd took an active role in a Construction Industry Research and Information Association (CIRIA) research project on the management of landfill sites and land contamination on eroding or low-lying coastlines (CIRIA 2013). The aim of this project was to prompt further work and raise the issue of eroding landfills (and other areas of land contamination) with policy makers and planners. Involvement in this project provided LLW Repository Ltd with increased awareness of the current understanding of landfill erosion and the associated regulatory framework. We consider that continued involvement in this work may be able to provide the company with further useful information to support the ESC. We recommend that LLW Repository Ltd maintains ongoing links with wider investigations into the characterisation, assessment and remediation of eroding historical landfills and incorporates relevant learning into the ESC (**Recommendation SUE44**).

The 2011 ESC provides elicited long-term performance values for the LLWR engineered barriers, but does not investigate or assess a wider range of long-term (several 1000s of years) engineered barrier degradation and evolution processes, that could impact repository performance before and during disruption by coastal erosion. To support the production of a response to ESC-FI-028 consideration should be given to these processes being further investigated. This might, for example, include work to improve understanding of cap soil erosion or the impact on the assumed cap vegetation as a result of changing climate.

Overall, we consider that LLW Repository Ltd has gained sufficient understanding of the nature of erosion processes and the response of the repository, so as to allow a comprehensive assessment of environmental impacts. Because of the levels of uncertainty associated with the nature and timing of repository erosion and the behaviour of the waste and associated engineering during the

erosion sequence, we consider that it is important that the company continue to develop their understanding of the repository erosion sequence and we set out our expectations in ESC-FI-028.

2.3.6. Site evolution uncertainty

The level of uncertainty associated with coastal disruption of the LLWR is high, arising at least in part from uncertainties associated with future climate change and the complexities of coastal change. We expect significant uncertainties in the timing and nature of coastal erosion to be appropriately constrained and considered within the 2011 ESC using a range of scenarios. We are satisfied that LLW Repository Ltd has appropriately taken into account a wide range of factors in concluding that the repository disposals are near certain to start being eroded on a timescale of a few 100 to a few 1000 years. By describing a range of possible timescales, LLW Repository Ltd has deliberately avoided the identification of a 'best estimate' value for the time of future site disruption within this range. This approach is appropriate, as it takes into account the level of uncertainty associated with the timing of coastal disruption.

The work to characterise the coastal erosion sequence presented in the 2011 ESC brought together science, modelling and expert opinion from a wide range of disciplines to define and conceptualise the coastal erosion exposure scenario. By using subject area experts, subject-specific peer reviews and the output of a peer reviewed science programme, LLW Repository Ltd has made sure that the 2011 ESC is based on reasonable data. The company has also identified those areas of the coastal erosion conceptualisation with the greatest uncertainty (rate and magnitude of sea level change) and has reflected the consequences of this uncertainty by developing a wide range of assessment scenarios.

LLW Repository Ltd has also appropriately recognised the presence of uncertainties in processes at global, regional and local scales. We accept that climate change and sea level change uncertainties are high; this reflects the nature of long-term climate predictions. We note that the timescale over which the 2011 ESC seeks to describe climate change and sea level change is far in excess of the typical 100 year predictions used to inform shoreline management and adaptation measures. As a result the level of uncertainty in these predictions is necessarily greater than that used for shorter-term decision making such as that used in Shoreline Management Plans (SMP).

The 2011 ESC describes this level of uncertainty associated with projections of climate and the implications on coastal change in the vicinity of the LLWR in the FEP and uncertainty tracking system (LLW Repository Ltd 2013a). LLW Repository Ltd indicates that it is content with the treatment of uncertainty relating to the nature and timing of erosion in the 2011 ESC and we agree. However, the company considers that there are major uncertainties in the morphology of the LLWR and its surroundings during coastal erosion, although these uncertainties will be difficult or impossible to reduce. The company has recognised the importance of these uncertainties and we consider that they have been appropriately addressed in cautious calculations of radiological consequences. However, we expect the ESC forward programme of work to further investigate FEPs with high levels of associated uncertainty and we set out our expectations in ESC-FI-008.

The 2011 ESC identified that the shoreline and hinterland around the LLWR may be subject to 1 or more erosion processes, which may include coastal erosion, inundation and fluvial erosion. We consider that the 2011 ESC does identify appropriate worst-cases for individual erosion processes. However, because of the potentially complex interactions of the identified processes, we recommend that LLW Repository Ltd considers investigation of the significance of interactions between erosion processes and associated uncertainties, including significant thresholds[11] (**Recommendation SUE45**).

LLW Repository Ltd assigns a low level of uncertainty to the FEPs that describe the physical characteristics of trench and vault structures and waste during the erosion sequence (LLW Repository Ltd 2013a). A relatively simplistic approach is used to characterise the degradation of

[11] Thresholds meaning stages within geomorphological processes, which when exceeded result in significant changes to the geomorphological processes, for example a change from an erosional environment to a depositional environment.

waste as it erodes, which does not fully take account of waste and engineering heterogeneity. We consider this approach sufficient to inform assessments, as it applies a conservative erosion rate to the erosion front. Nonetheless, we consider that there may be benefits in improving understanding of the implication of the physical form of the eroding waste and repository structures as they enter the beach environment and are subject to wave action. This may allow the further development of a fuller understanding of the behaviour of waste and repository materials after initial erosion from the repository. Any such further work may help to confirm that the assessed scenarios are suitably constrained by assumptions on erosion rates and that all reasonable PEG interactions during the erosion sequence have been considered. We have set out our expectations in ESC-FI-028.

Uncertainty associated with the nature and timing of coastal erosion is likely to remain high throughout the period of authorisation. We are satisfied with LLW Repository Ltd's identification and use of uncertainty in the conceptualisation of coastal erosion. Taking these factors into account, we consider that LLW Repository Ltd has assessed an appropriate range of potential future climate, sea level and erosion change scenarios to appropriately inform the radiological assessment (LLW Repository Ltd 2011b and Environment Agency 2015e).

Due to the importance of coastal evolution scenarios in the 2011 ESC and to inform the long-term planning of the LLWR we consider it important that uncertainties are reduced wherever practicable and proportionate to do so. This could be through monitoring, further site investigation, engagement with international long-term climate change investigations, improved modelling or conceptualisation. We describe our expectations in a number of FIs including ESC-FI-004, ESC-FI-008 and ESC-FI-028.

2.3.7. Shoreline Management Plan

The shoreline management plan (SMP) is a strategic level document developed by the local authorities, that sets out shoreline management policy and approach for the next 100 years. A SMP is in place for the coastline in front of and adjacent to the LLWR (Halcrow 2010b, c). The SMP for the Drigg coastline involves no active intervention, allowing natural erosion of the current coastline. It recognises the presence of the LLWR and recommends continuing reviews, examining the consequence of up to date climate change predictions.

Coastal defences are not part of the LLWR site development plan (SDP), as discussed in Section 2.3. It is also important, however, to recognise that another organisation could choose to create coastal defences on the west Cumbrian coast at some point in the future. The impact of the construction of sea defences or other changes to the current coastal sediment environment could change the behaviour and response of the coastline adjacent to the LLWR. Of particular relevance would be any developments that may change the current sediment budget assumptions that inform the site evolution models. During the period of authorisation we would expect the potential impact of major coastal developments and defence construction at locations adjacent to the Drigg shore front to be identified during the SMP strategic planning and the short-term development process. Where potential interactions or impacts could occur related to the LLWR, we would expect the 2011 ESC to be updated to take account of any identified change on the local coastal and sediment processes. It is therefore important that LLW Repository Ltd identifies any significant changes to sea defences on the coastline to the north and south of Drigg and assesses the implications in future updates of the ESC. This should include changes to the current SMP that could impact on the LLWR (**Recommendation SUE46**).

LLW Repository Ltd will need to maintain an awareness of the SMP throughout the period of authorisation. In doing so, the company should liaise with the Environment Agency, the relevant planning authorities and the local authority with responsibility for developing the SMP.

2.3.8. Extended disposal area

LLW Repository Ltd assesses the impact of coastal disruption of the EDA separately to that of the RDA (LLW Repository Ltd 2011g). This assessment used the same source information and modelling, but took into account the extended frontage of the EDA, that is located further away from the current coastline. The assessment identified an increased likelihood of direct erosion rather than undercutting for the EDA vaults. The company assessed the impacts associated with both the reference (north-west to south-east) erosion alignment and a southward approaching

oblique alignment. As with the RDA, we consider that these potential erosion alignments are appropriate.

We consider that there is a potential for the longer erosion front provided by the EDA vaults to influence the erosion sequence, by increasing the ratio of waste to natural materials and the total amount of waste entering the environment. As the LLWR erosion sequence is further considered in the future, we consider that LLW Repository Ltd should assess the impact of the total EDA vault waste volume on the erosion sequence. Although any impact is likely to be small, because of the differences in waste age between the RDA and EDA, we recommend that the company should also consider the implications of differences in degradation state on erosion between the newer EDA vault waste and with the older RDA vault waste (**Recommendation SUE47**).

2.3.9. Forward programme

The conclusions of our review of the site evolution sequence highlight the importance of LLW Repository Ltd maintaining continued awareness of developments in climate change and coastal erosion processes throughout the period of authorisation. It is therefore important that LLW Repository Ltd's forward programme of work sets out mechanisms for maintaining awareness or undertaking further development work as necessary and that triggers for the beginning of further site-specific investigations are considered.

In ESC-RO-SCM-005 we asked LLW Repository Ltd to set out a forward work programme to support the ongoing development of the ESC. Although further detail was provided, the company's response did not set out how the forward programme would be used to inform, maintain and improve their understanding of the predicted site evolution sequence and reduce current uncertainties (Cummings 2011). We will expect the forward work programme to address these issues, along with other work required to support the further development of the ESC (see ESC-FI-004). We anticipate that significant further supporting information will become available over the years from both generic and targeted climate change science work carried out nationally and internationally. LLW Repository Ltd should continue to engage with relevant long-term climate change programmes, including those supporting radioactive waste disposals, for example the IAEA's MODARIA project (see Section 2.3.2).

Both LLW Repository Ltd and ourselves identify the need for ongoing coastal monitoring and surveying throughout the period of authorisation. This monitoring will need to be able to characterise the nature and extent of coastal erosion, both between major surveys and in response to significant storm events. Regular monitoring (for example at 5 to 10 yearly intervals) will make sure that the observed evolution of the coast can be effectively used to inform future ESCs. Coastal erosion monitoring should be carried out using known reference points at sufficient frequency to allow identification of coastal changes. Where appropriate, high accuracy survey techniques such as LIDAR[12] should be considered.

The company has already instigated an annual coastal erosion survey programme (Halcrow 2013b). However, the company should review this programme to make sure that it takes full account of our review of the 2011 ESC. We have asked the company to set out its proposals for coastal erosion monitoring in ESC-FI-019.

2.4. Environmental monitoring

Requirement R14 of the GRA states, ‘In support of the environmental safety case, the developer/operator of a disposal facility for solid radioactive waste should carry out a programme to monitor for changes caused by the construction, operation and closure of the facility’ (GRA Paragraph 6.4.31).

LLW Repository Ltd has a substantial programme of monitoring that covers both monitoring of environmental media and the performance and evolution of the LLWR. This programme has been

[12] LIDAR is a remote sensing technology that measures distance by illuminating a target with a laser and analysing the reflected light.

refined over the years to meet the changing needs of the LLWR as it has developed, as well as to take account of changing regulatory requirements.

LLW Repository Ltd describes its environmental monitoring programme in LLW Repository Ltd (2011d). This report is supplemented by a number of Level 3 documents describing specific aspects of the monitoring programme (Carson 2010, Speed and Fretwell 2010, Shevelan 2011 and Hayes et al. 2011). We also took into account annual reporting information supplied in response to the following requirements from Schedule 9 of the LLWR environmental permit (Environment Agency 2010):

- Requirement 7: 'The Operator shall establish a comprehensive programme of monitoring to confirm the integrity of both the interim cap covering past disposals and the bentonite cut-off wall constructed to the north and east end of the disposal area.'
- Requirement 8: 'The Operator shall establish and implement a monitoring programme to determine the extent of groundwater contamination around the site arising from LLW disposals. A report of the programme and how the results have been used to both inform risk management options for the site and build confidence in safety assessment models, shall be provided to the Agency.'

Although some of these reports were presented with the 2011 ESC, they are standalone submissions and had been separately reviewed by ourselves during routine regulatory interactions.

Our review of the provision and use of monitoring within the 2011 ESC focused on the following areas, in line with Requirement R14 of the GRA:

- provision of a reasoned and proportionate environmental monitoring programme to support the development and maintenance of the ESC throughout the period of authorisation
- consideration of the appropriate use of past environmental monitoring information in the ESC, including both baseline information and assessment of the environmental impacts associated with past permitted disposals
- provision of a performance monitoring capability to demonstrate compliance with authorised discharge limits and performance expectations set out in the environmental permit
- examination of the use of monitoring information in the calibration, refining and checking of environmental models, including an audit of groundwater models used in the ESC
- characterisation of the environment and establishment of a baseline before the construction of future vaults
- establishment of a comprehensive long-term monitoring strategy throughout the period of authorisation

Our review has covered:

- the planning and development of the statutory and non-statutory monitoring and sampling programme
- the construction, maintenance and operation of monitoring infrastructure
- quality systems for the collection, analysis and use of environmental information
- use of the environmental monitoring data in the ESC
- environmental reporting

We require the monitoring programme to evolve over the period of authorisation to take into account changes in the LLWR and monitoring objectives. As part of our routine regulatory interactions we will continue to review and comment on changes to the LLWR environmental monitoring programme via ongoing liaison with the company, via environmental reporting requirements and as part of the ESC review process.

2.4.1. Current environmental monitoring programme

LLW Repository Ltd currently has an extensive environmental monitoring programme in place. The programme provides coverage of all environmental media and includes identified sources, pathways and receptors. Environmental monitoring is carried out for a wide range of objectives including to:

- inform and validate the ESC
- provide statutory environmental performance and discharge information
- meet project specific objectives

The information presented with the 2011 ESC represents a small proportion of the wider environmental monitoring and sampling programme carried out at the LLWR. This larger body of information is currently subject to routine regulatory scrutiny via both Schedule 9 Requirement 8 reporting (LLW Repository Ltd 2007, 2008c, 2009b, 2010b, 2013d and Serco 2011b, 2012) and via regulatory compliance reporting. We also periodically undertake audits of environmental data collected by LLW Repository Ltd (see, for example, Environment Agency 2011a and Clarke 2011).

We do not specifically comment here on the annual environmental monitoring results presented in the 2011 ESC, as we had previously reviewed and commented on this information as part of our routine regulatory interactions. However, where appropriate, we reviewed LLW Repository Ltd's understanding of the current repository performance and any changes in environmental discharges since the 2002 PCSC.

LLW Repository Ltd currently undertakes a comprehensive environmental monitoring and sampling programme measuring both radiological and non radiological parameters. The main measured environmental media are:

- groundwater height and quality
- surface water flow and quality
- leachate volume and quality
- concentrations of radioactivity in environmental media

Other monitoring activities include monitoring of coastal change, meteorological data, landfill gas, beta/gamma dose rates, ambient air activity, radon measurements in enclosed spaces, direct radiation measurements and re-assurance monitoring of radioactivity in grass, soil and milk samples. None of this monitoring has identified any significant causes for regulatory concern in the period leading up to the 2011 ESC submission (LLW Repository Ltd 2011d) or subsequently.

In addition to reviewing the 2011 ESC we undertook the following interactions with LLW Repository Ltd:

- review and provision of feedback on submitted environmental monitoring information
- targeted reviews and audits
- ongoing reporting of monitoring issues at liaison meetings

We will continue interaction with LLW Repository Ltd and review any significant changes to the monitoring programme or the measured environmental performance. Under the current environmental permit, LLW Repository Ltd is required to notify us of any significant changes.

Before and during our review of the 2011 ESC, we undertook the following activities to gain confidence in various aspects of the system:

- In relation to environmental monitoring we carried out a targeted audit of the planning, collection, analysis and reporting processes, monitoring infrastructure and linkages with the LLW Repository Ltd ESC Project Team (Environment Agency 2011a and Clarke 2011). This review concluded that environmental monitoring is carried out within a comprehensive and robust quality system capable of generating and managing high quality environmental monitoring data. We confirmed that the environmental monitoring data are effectively shared with the LLW Repository Ltd ESC Project Team[13].
- We gained confidence in the management and storage of environmental monitoring information via routine regulatory interaction.

[13] Since the audit, the LLW Repository Ltd environmental monitoring team has been incorporated into the same team as the ESC Project Team improving links further.

- We held a technical meeting with LLW Repository Ltd to investigate detailed aspects of non-radiological monitoring and equivalency with applicable landfill legislation. The meeting clarified the approach LLW Repository Ltd intends to adopt for non-radioactive gas. We discuss the outcomes further in Section 2.4.8.
- We interacted with LLW Repository Ltd to assist in the development of an assessment framework for the long-term non-radioactive groundwater discharges identified in the 2011 ESC. This resulted in proposals for further development work in the future (see ESC-FI-006).

We consider that LLW Repository Ltd's current site environmental monitoring programme and the associated systems and procedures are of high quality. The company has made significant improvements to its environmental monitoring programme and infrastructure since the 2002 ESCs. We are confident that the data derived from the environmental monitoring programme are of suitable quality and undergoes appropriate scrutiny before use in the 2011 ESC. This has given us confidence in the robustness of the monitoring information presented in the 2011 ESC.

2.4.2. Environmental monitoring provision

LLW Repository Ltd's current statutory monitoring requirements for radioactivity in groundwater, surface water and aqueous discharges are outlined in the Compilation of Environment Agency Requirements (CEAR) supporting Environmental Permit YP3293SA (Environment Agency 2009c). Further requirements for non-radioactive monitoring of aqueous discharges are outlined in the discharge consent (NPSWQD002191). Following a review of site monitoring in 2008, the various strands of environmental monitoring have been brought together as a single monitoring and sampling programme. Statutory monitoring is therefore included within a wider programme of environmental monitoring, covering both the disposal locations on LLWR, as well as the wider site which includes land use associated with the former Royal Ordinance Factory and the historic plutonium contaminated material stores, as well as some off-site locations.

In line with the expectations of the GRA, LLW Repository Ltd has defined a series of performance measures to monitor environmental impacts via leachate, or to surface waters and groundwater as a result of contaminant release from the LLWR. These include control levels to assess whether the facility is performing as designed and to identify potential adverse trends, as well as compliance or trigger levels that mark the point at which significant environmental impacts are assumed to have occurred.

To assess the non-radioactive impact of the LLWR on the environment, LLW Repository Ltd developed screening criteria for the most relevant non-radioactive determinands. The company designated these criteria as ‘LLWR Assessment Standards' (LLWRAS), and they provide screening levels for leachate, groundwater and surface water quality (LLW Repository Ltd 2011d). LLWRAS are based on the most restrictive of the UK Drinking Water Standards (DWS) and Environmental Quality Standards (EQS) and are in addition to the statutory (CEAR) discharge limits. We have reviewed the LLWRAS and note that they are in some cases inconsistent with our guidance on hydrogeological risk assessment for landfills (Environment Agency 2011b). For example, assessment standards for hazardous substances should be based on Minimum Reporting Values (MRV) where available or background concentrations, not EQS or DWS, as their entry to groundwater should be prevented. We identified the need for further development of non-radioactive groundwater sampling provision and set out our expectations for the provision of more appropriate criteria needed to support the future production of non-radiological hydrogeological risk assessments in ESC-FI-006.

Our review of the 2002 PCSC identified the need to regularly monitor the groundwater between the site and the coast to evaluate discharges from both upper and regional groundwater to the coastal area and to the north-west of the site (see IAF GEO_003.2 in Environment Agency 2015h). Consistent with our request and the identified need to support the ESC, LLW Repository Ltd installed a number of new groundwater monitoring boreholes downgradient of the site, between the LLWR and the coast. These boreholes are capable of providing robust and comprehensive groundwater monitoring information from both the upper and regional groundwater. We recognise the practical constraints in the construction of site investigation and monitoring boreholes within this area because of its designation as a SAC and SSSI. Irrespective of these improvements and access constraints, we still believe that there remains scope for improvement of site investigation

and monitoring capability for the land between the LLWR and the coast (see Section 2.2 and Recommendation SUE3).

We reviewed each of the annual submissions against Requirement 8 of Schedule 9 of the current environmental permit when they were submitted. We can confirm that they provide an effective way of collating and presenting annual information between ESC reviews and can be used to scope investigations where trends are identified. The varied (updated) environmental permit for the LLWR will include requirements for the reporting of the output of environmental monitoring programmes at an appropriate frequency. These reports will be in addition to and inform the reporting of environmental monitoring presented in major ESC updates.

We consider that the annual submissions against Requirement 7 of Schedule 9 of the current environmental permit demonstrates that the cut-off wall continues to act as a barrier to contaminant migration in the upper groundwater on the eastern and northern boundary of the trenches and that there has been no observable deterioration in its performance. The cut-off wall will need to continue to prevent eastern and northern migration of trench contamination throughout the period of authorisation. We anticipate that the varied (updated) environmental permit for the LLWR will include requirements for LLW Repository Ltd to continue regular reporting of the performance of the eastern and northern cut-off wall, with the specific objective of demonstrating continued containment of trench leachate.

Around 2010, LLW Repository Ltd improved the perimeter drainage infrastructure of the trenches and the measurement capability of trench probes. After the collection of 3 years of data, the company was able to produce an improved trench water balance model, better capable of quantifying the volume of rainfall entering the trench disposals. The results of the water balance model are reported in the more recent submissions against Schedule 9 Requirement 7 (for example Jefferies 2011 and LLW Repository Ltd 2013b). This work has shown that the interim trench cap is performing less well than assumed in the 2011 ESC and has led to a programme of work to assess the need to and as necessary improve, the interim trench cap before the placement of the final cap. The calculation of the trench water balance could help validate the performance of any further restoration measures installed before the construction of the final cap. We will expect the company to continue to monitor the performance of the interim cap and any subsequent final cap, throughout the period of authorisation.

We consider that monitoring provision within and adjacent to the trenches is limited, which constrains the information available on the interaction between trench leachate and shallow groundwater and the understanding of the evolution of the trench disposals. We recognise that this is a reflection of the age of the trenches. However, we consider that the monitoring capability adjacent to and within the trench disposals would benefit from increased functionality, both before and after the placement of the final capping system. Improved monitoring may be necessary to gain information, for example: on water entry to the trenches via the cap or via shallow groundwater; to quantify the output of leachate into groundwater and collection systems; and, to quantify any cap infiltration that does not enter the waste mass (**Recommendation SUE48**).

We require LLW Repository Ltd to consider the need for and practical constraints associated with, the provision of trench leachate and adjacent shallow groundwater monitoring before and after the placement of the final capping system (see ESC-FI-023).

We conclude that LLW Repository Ltd has sufficient monitoring infrastructure and programmes to support the 2011 ESC and for current needs. However, as noted above, there is scope for further improvements that the company should consider to maintain the application of BAT. As the LLWR is further developed it is important that the company continues to review monitoring capability and maintain alignment with future ESC (and other) requirements.

2.4.3. Non-radiological groundwater monitoring

Since the 2002 PCSC, LLW Repository Ltd has widened the scope of the environmental monitoring programme to incorporate the collection and interpretation of samples to assess the impact on groundwater from non-radiological contaminants. The company reviews the non-radiological monitoring data in Speed and Fretwell (2010). It concludes that there is limited evidence of non-radiological contamination of groundwater and surface water at the LLWR.

However, there are some occurrences of organic compounds such as hydrocarbons, toluene, phenol and explosives residues. A number of inorganic substances are also observed at concentrations above the LLWRAS, including ammonium, arsenic, iron, manganese, nickel, nitrate, nitrite and sulphide. We discuss the assessment of non-radiological impacts further in Environment Agency (2015e).

Speed and Fretwell (2010) consider that baseline concentrations of some groundwater contaminants appear elevated. We recommend that LLW Repository Ltd takes background groundwater concentrations of contaminants into account within the LLWR non-radiological groundwater monitoring programme (**Recommendation SUE49**). This would allow clearer demonstration of whether measured values exceeding standards are the result of discharges from the disposals, historical land uses on the LLWR site, or whether they are a product of natural groundwater quality or up gradient contamination (for example, agricultural activities).

Because the elevated background groundwater concentrations of some non-radiological contaminants could be the result of activities external to the LLWR, such as agriculture, we recommend that LLW Repository Ltd considers whether further sampling of up gradient groundwater is necessary to ensure the timely and effective identification and quantification of offsite sources (**Recommendation SUE50**).

The non-radiological assessments within the 2011 ESC (LLW Repository Ltd 2011f) need to be appropriately supported by monitoring data. We consider that monitoring data have been appropriately used to inform the assessment and that these data are largely appropriate. However, we do consider there is some scope for improvement in the future. For example, sampling locations should be identified that are analogous to those used as landfill assessment compliance points. This will aid in future assessments of non-radiological impacts and support any future work to demonstrate that the level of protection provided by the LLWR is no less stringent than that which would be applied at a non-radioactive landfill.

We set out our requirements for improvements to the non-radiological risk assessment in ESC-FI-006, including expectations regarding monitoring.

2.4.4. Monitoring of environmental radioactivity

As a result of our review of the 2002 ESCs, we asked LLW Repository Ltd to undertake a sampling and monitoring campaign to establish background levels of radioactivity in and around the LLWR site (see IAF BIO_004.1 in Environment Agency 2015h). Since then, the company has carried out further monitoring to support its claim in the 2011 ESC that it has 'an understanding' of background levels of radioactivity (LLW Repository Ltd 2011d). We are satisfied that sufficient information has been gathered and assessed to support the conclusions reached within the 2011 ESC. However, we have not yet seen a full demonstration that this is adequate in all respects.

LLW Repository Ltd notes that, as monitoring data are not available before 1959 when trench disposal began, to provide true background levels it has used monitoring data for the past 2 years to define the current baseline levels for the calculation of control and compliance levels (LLW Repository Ltd 2011d). Although there is a substantial database from a wide range of environmental media, the company has not attempted to establish true background concentrations from this data. However, it suggests that the contribution to environmental radioactivity detected in the geographical area of the LLWR site is masked by the contribution from Sellafield, in a similar way to that for non-radioactive contaminants (Thorne and Schneider 2011). Furthermore, we note that the non-human biota assessment of the current radiological impacts to the ecosystems local to the LLWR draws heavily from relatively old monitoring data, cited by Eden and Barber (2007) and studies not primarily intended for the assessment of the impact of the LLWR (see IRF ESC-RO-ASO-001 and Environment Agency 2015e). We recommend that LLW Repository Ltd makes further efforts to improve understanding of background levels of radioactivity in and around the site in the future ESC (**Recommendation SUE51**).

2.4.5. Monitoring of vault leachate

In our review of site optimisation and engineering we identify the need for a leachate management strategy covering the vault disposals and other areas of leachate management (Environment Agency 2015d). We consider an integral part of the management strategy to be the ability to

monitor the volume and composition of leachate across the vaults throughout the period of authorisation. The 2011 ESC does not set out proposals for the monitoring and sampling of vault leachate before and after the placement of the final capping during the period of authorisation, but this is addressed by the LLW Repository Ltd forward programme of work (Cummings 2011, Shaw 2013).

We recognise that the concentrations of radioactive and non-radioactive contaminants in the vault leachate will be very low throughout much of the period of authorisation, reflecting the level of containment provided by the containers and grouted waste-form and the presence of large volumes of rain water. However, we nonetheless expect vault leachate to be collected and analysed to inform the ESC as far as possible.

Following on from the 2011 ESC and before final capping there is a need for further development and detailed optimisation of the leachate management strategy, including vault leachate monitoring. We set out our expectations in this area within ESC-FI-023. We expect this and other work to address future needs for monitoring infrastructure, sampling and analysis to support the ESC and site understanding. This could include, for example, representative information on the height, volume and composition of leachate from the whole footprint of the vaults.

2.4.6. Monitoring of trench leachate

Leachate generated within the trenches is currently collected along their bases. Leachate flows by gravity from the trenches to collection points and on to the marine holding tank for sampling and discharge. Within the trenches there is no continuous leachate collection pipe work, although a pipe was placed through the lateral firebreaks of some trenches. Approximately 60 vertical gas probes are located across the trenches and are used to monitor gas and leachate composition and leachate height. The probes were installed after the construction of the trenches and their bases are located at or near the base of the trenches.

The 2011 ESC engineering design (LLW Repository Ltd 2011h) does not identify the need for replacement of the trench leachate management infrastructure, or the ability to remotely monitor leachate and trench conditions. Because the SDP seeks to minimise water ingress into the trench waste and facilitate de-saturation of it during the period of authorisation, it is important that it can be monitored (for example for leachate level, composition and gas) and management actions implemented if required. Within their forward programme of work (Cummings 2011) LLW Repository Ltd have committed to review their monitoring programme. We consider that as part of this work and wider engineering programmes (Shaw 2013), the company should develop a leachate management strategy, including monitoring needs, that is capable of providing necessary trench leachate and gas monitoring within each individual trench both before and after installation of the final cap, demonstrating a fully optimised approach. We detail our expectations in ESC-FI-023. The proposals should provide reassurance that the assumptions regarding the evolution of the trench waste in the 2011 ESC are reasonable.

As part of ESC-FI-023, we have asked LLW Repository Ltd to identify its objectives for the monitoring of trench leachate and to set out a monitoring programme for trench disposals before, during and after the placement of the final cap, to the end of the period of authorisation. The monitoring capability should consider:

- the ability to measure representative leachate heights in each discrete trench throughout the period of authorisation, taking account of the potential for isolation of areas of trenches
- provision of a mechanism to measure the performance of the current interim trench cap (and any interim solution applied before installation of the final trench cap) and the final capping system
- the ability to measure relevant trench parameters, such as temperature, moisture content and gas composition and volume

2.4.7. Near field monitoring

An important element of an ESC is the ability to demonstrate a good understanding of the long-term evolution of the waste and to reduce uncertainties associated with evolution processes such as gas generation and corrosion processes. LLW Repository Ltd has assessed the behaviour and

evolution of the waste throughout the life of the LLWR in the 2011 ESC. With the exception of leachate level and composition data, the majority of this understanding was derived from modelling or elicitation. In the future, we expect the company, where practicable, to place an increasing emphasis on use of monitoring information on the evolution and condition of the near field environment, including the waste form, grout, container and wider LLWR conditions.

We consider it is important that LLW Repository Ltd further develops a forward programme of work to understand conditions within the vaults and trenches before and after placement of the final cap. We note that the company has already developed a forward programme which includes maintenance of near field understanding (Cummings 2011). This information should enhance understanding of vault and trench conditions and inform projections of the evolution of the waste mass and surrounding near field, to inform future updates of the ESC. We have asked LLW Repository Ltd to prepare and implement a near field experimental and monitoring programme capable of providing sufficient understanding of the vault and trench environments throughout the period of operation in ESC-FI-018. As part of this programme, the company should consider potential ways of monitoring waste form, grout and container behaviour either within the vault environment or in dedicated ex-situ trials or experiments. The programme might include, for example, the monitoring of physical, chemical, biological and geochemical parameters.

A near field monitoring programme should:

- have clearly defined objectives
- help confirm performance assumptions within the ESC
- support future development of the ESC

We expect any requirements for near field monitoring to be incorporated in the ESC forward programme.

2.4.8. Landfill gas monitoring and characterisation

Within the 2011 ESC LLW Repository Ltd has not identified the need for active management of landfill gas generated from either the vaults or trench disposals during the period of authorisation. This management approach relies on the assumption that little putrescible material has been disposed of and that the passive gas collection and dispersion systems will effectively remove radioactive and non-radioactive gas from the capped repository during the period of authorisation, to the extent necessary to prevent damage to the engineered barriers.

We held a workshop with LLW Repository Ltd which included discussion of monitoring and characterisation of the LLWR gas composition and generation rates in the short and longer-term. Specifically, we sought an improved understanding of the company's use of the near field GRM in the 2011 ESC to project landfill gas production volumes and generation rates during the period of authorisation, in particular during placement of the final cap. This was with a view to understanding the adequacy of the proposed passive management of landfill gas during the period of authorisation.

In response LLW Repository Ltd commissioned a report that included theoretical gas generation rates (Baker 2012) and presented a historical paper outlining gas generation rate and volume assumptions (Arup 2000). When combined with an understanding of the age and composition of the waste from LLW Repository Ltd's inventory assessment (LLW Repository Ltd 2011i), we have gained sufficient assurance that landfill gas from the trench disposals will be generated at low rates and could be passively managed throughout the period of authorisation (for example, based on the low predicted amounts of putrescible waste to be disposed at the LLWR). The 2011 ESC describes at a high level a number of objectives for the passive management of gas before and after the period of authorisation. However, we consider these objectives could be further underpinned and a gas management strategy further developed before construction of the final cap. We request this in ESC-FI-024.

Although landfill gas production rates and flow have in the past been shown to be low and are expected to continue to be low, we consider it essential that sufficient monitoring and sampling capability is incorporated into the trenches and the vaults to inform the assessment of non-radioactive and radioactive gases in future updates of the ESC. Gas monitoring capability will

improve understanding of current and future gas generation and flow rates, to better inform the engineering design and validate the assumptions used in the 2011 ESC. Development of a gas management strategy should consider gas collection and sampling infrastructure requirements for both bulk and trace gases.

To construct the final capping system for the trenches, a significant loading will be placed onto the past trench disposals as part of surcharging[14]. The placement of surcharging material onto the trench disposals will load and squeeze the trench waste. It is probable that the gas generation characteristics of the trenches will change as a result of the placement of surcharging materials and the subsequent final cap. During the placement of the surcharge materials and final cap, LLW Repository Ltd will need to have appropriate measures in place to monitor gas generation rates and volumes and demonstrate that the resulting impacts are being managed in accordance with BAT.

We conclude that LLW Repository Ltd has demonstrated that landfill gas generation rates will be low and can be managed passively. Further work is required as the site develops and capping proceeds. We expect development of a gas management and monitoring strategy to be in place in advance of the first phase of final capping.

2.4.9. Monitoring complexants

The current LLWR environmental permit and waste acceptance criteria (WAC) do not allow the disposal of complexing and chelating agents (referred to here as complexants). However, LLW Repository Ltd has submitted an application to the Environment Agency to vary its environmental permit so that complexants can be disposed of to the LLWR, although in limited quantities in some cases (LLW Repository Ltd 2013e). If permitted, LLW Repository Ltd would subsequently amend its WAC to allow disposal of complexants.

Amino polycarboxylic acids such as ethylene diamine tetra-acetic acid (EDTA) are a class of complexants that present a specific challenge to the LLWR. These materials are known to enhance the solubility and reduce the extent of adsorption of a number of important radionuclides and other non-radioactive species. The presence of these complexants could therefore increase risks via the groundwater pathway. This is discussed within the 2011 ESC (LLW Repository Ltd 2011j, 2013c).

We note the assessment model input reference concentration for EDTA is based on limited monitoring information. For example, the reference EDTA concentration for the trenches is based on only 5 samples of trench leachate. Although we consider the reference concentration used to be adequate, given the other conservatisms applied to this assessment, we recommend that further samples of trench leachate are analysed to verify and build further confidence in the EDTA reference concentration and those of other relevant complexants (see ESC-FI-009). Throughout the period of authorisation, the monitoring programme should include the provision of periodic sampling to ensure the ESC assumptions on complexant behaviour and concentrations remain valid, particularly for amino polycarboxylic acids.

2.4.10. Monitoring of colloids

LLW Repository Ltd has previously sampled and analysed for colloidal material and radionuclides that may be associated with them (LLW Repository Ltd 2011j) and this has established a baseline understanding. In our reviews of both the 2002 ESCs and the 2011 ESC, we have identified the need for ongoing periodic measurements to determine if activity is associated with colloids (see IAF GEO_003.8, IAF GEO_004.1 and IAF GEO_004.2 in Environment Agency 2015h). In information submitted after the 2011 ESC, the company undertook a one-off study to provide improved understanding of colloids and contaminant transport (Peachey and Shevelan 2012). We support the company's proposals to periodically carry out simple measurements to determine if the activity associated with particulates is linked to colloids.

[14] Surcharging is the placement of material over the top of the waste prior to the engineered cap being placed over the trenches, to induce settlement in the waste materials and thus limit the extent of settlement that the engineered cap will be initially subjected to.

Although we accept that there is currently an adequate understanding of colloids for the purposes of the 2011 ESC assessments, we consider that a proportionate programme of ongoing sampling and analysis for colloidal material and associated radionuclides is of value. Such a programme should address both the near field and geosphere and should have the objective of increasing and maintaining confidence in the validity of conclusions regarding the presence of colloidal material and their ability to enhance contaminant transport of radionuclides. We outline our expectations in ESC-FI-015.

2.4.11. Container condition monitoring

The ISO freight containers within which waste is disposed of provide containment and isolation before capping and containment, chemical conditioning, stability and void filling after capping. It is important that their condition is monitored and assessed before capping. Any such monitoring needs to demonstrate effective isolation of the waste, that container drainage features are functioning and that the extent and nature of container degradation does not significantly impact on their containment function or ability to offer stability following capping. We expect LLW Repository Ltd to demonstrate the containers provide BAT regarding waste containment before capping.

We first raised the issue of container condition monitoring and sampling in ESC-RI-INF-005 (see Environment Agency 2015c). In response, LLW Repository Ltd carried out an initial inspection of selected containers and the grout contained within (Jefferies 2012). The company proposes that it carries out further inspections of the nature and extent of any future container degradation annually. The company should ensure the inspections provide confidence that no further significant deterioration that could impact on the ESC assumptions is happening, or allow corrective action to be taken if necessary and that BAT continues to be applied for the containment of the waste and therefore also minimisation of discharges.

We expect LLW Repository Ltd to use the results of the inspections to inform further optimisation of the LLWR design regarding waste container exposure, minimisation of waste container degradation and discharges from the vaults before final capping (see ESC-FI-025). The inspections will also inform cap settlement assessments being carried out, against which we have outlined our expectations (ESC-FI-001 and Environment Agency 2015d).

We expect LLW Repository Ltd to continue to monitor container condition to the extent necessary to inform the 2011 ESC and to demonstrate environmental safety throughout the period of authorisation, where containers remain uncapped and accessible. In particular we expect a good understanding of the Vault 8 containers, which have been exposed for a significant period of time, to be maintained up to the point of capping. We will review the implementation of container monitoring through our future routine regulatory activity.

2.4.12. Tritium monitoring

As a result of past authorised disposals to the trenches, an extensive plume of tritium has formed in the groundwater underlying the LLWR and has migrated in a largely westerly direction away from the trenches[15]. Since the 2002 PCSC was published a large body of work has been carried out by LLW Repository Ltd to understand the source of the tritium and the nature and extent of the groundwater contamination plume.

Tritium concentrations in groundwater have significantly decreased since emplacement of the interim trench cap and cut-off wall between 1988 and 1995. However, a plume can still be seen in the shallow and regional groundwater down-gradient of the disposal site (BNFL 2007, LLW Repository Ltd 2008a, 2009a, 2010a, 2013b and Serco 2011a). We consider the implications of this tritium plume elsewhere (Environment Agency 2015e).

We consider it important that LLW Repository Ltd continues monitoring of tritium throughout the period of authorisation to:

[15] Prior to the installation of the perimeter cut-off wall to the north and east of the trench disposals, tritium contamination was also migrating to the north and east within the shallow groundwater.

- build confidence in understanding of the remaining trench tritium inventory, as far as is reasonably practicable
- review the spatial extent and trends in the current tritium groundwater plumes
- help understand the impact of the placement of surcharging material and the final trench cap placement on tritium remaining within the trenches
- indicate the performance of the eastern and northern cut-off wall
- review and improve understanding of LLWR groundwater flow and contaminant transport models
- demonstrate tritium monitoring data are consistent with LLWR groundwater flow and contaminant transport models
- support assumptions made in the 2011 ESC and in particular the associated habitats assessments about potential groundwater receptors within the protected habitats on the western edge of the site and within the Drigg dune system

We have asked LLW Repository Ltd, as part of the development of a forward programme and monitoring strategy, to outline how future tritium monitoring will meet these objectives in ESC-FI-002.

Before the emplacement of surcharging material on the trenches as the final cap is constructed, we will expect LLW Repository Ltd to consider possible releases of other contaminants into the groundwater environment as the waste is squeezed and to consider how BAT are being applied. We recommend that the company reviews its tritium monitoring capability before the placement of surcharge material onto the trench disposals (**Recommendation SUE52**).

2.4.13. Extended disposal area monitoring

The 2011 ESC does not discuss specific monitoring and sampling requirements for the EDA. We consider that this is reasonable given the significant timescales proposed before construction, during which time significant further development and learning is likely to have taken place. We consider that it is reasonable to assume that the RDA monitoring strategy can be extended to cover the EDA vaults and the extended operational period.

Due to the increased footprint of the EDA we expect LLW Repository Ltd to carry out groundwater monitoring over a wider extent than it currently provides. We would also expect site investigations to cover the proposed footprint before construction of Vaults 15 to 20. In particular, the site investigation and monitoring should take account of the potential presence of chemical and radiological contamination in the EDA footprint derived from past and ongoing site activities.

We note that the construction of EDA vaults to the south of the trenches would isolate the current trench leachate collection pipe outlets. This is an issue that should be considered as part of the leachate management strategy (see ESC-FI-023). We also note that the construction of vaults in the EDA footprint would remove some existing groundwater monitoring points. LLW Repository Ltd should consider the need for equivalent replacement of any groundwater monitoring points as necessary to support the monitoring strategy.

Due to the extended operational period of monitoring infrastructure (for example the marine holding tank sampling equipment and boreholes), LLW Repository Ltd needs to consider future requirements for upgrade, renovation or replacement, to make sure of its continued functionality throughout the period of authorisation. We expect the company to take into account the extended operational period of the site in the design of monitoring infrastructure and strategies (**Recommendation SUE53**).

2.4.14. Use of monitoring data in the ESC

The ESC needs to use appropriate environmental monitoring data to inform the conceptualisation of the site and the behaviour of disposals and to validate ESC performance assumptions. The nature and extent of environmental information available for use in the ESC will be a reflection of the stage of development of the repository, or elements of the repository.

The trenches have an extensive environmental monitoring data set reflecting the age of the disposals. These data have been used in the 2011 ESC to support the conceptualisation of the

trench disposals and inform and validate assessments. The monitoring programme also provides a baseline understanding of the environmental setting of the disposals.

The vault disposals have been optimised to deliver containment of waste within the ISO freight containers. This means that representative leachate will not become available for an extended period. As a result, there is less scope to gain useful information on the vault disposals which is representative of likely future behaviour. Leachate characterisation for the vaults is therefore at an early stage. In particular, because of the lack of a representative leachate derived from the containerised waste, there is currently no leachate source term for the vault disposals for use in assessments. Therefore, for the vaults, our review focused on the identification of future monitoring requirements and strategies corresponding with appropriate environmental pathways identified in the 2011 ESC. As site-derived information becomes available we expect future updates of the ESC to make use of this. As noted in Sections 2.4.5 and 2.4.7, we consider that LLW Repository Ltd needs to develop its programme for the collection of monitoring data from the vaults during the period of authorisation.

Section 4.3 of the Level 2 monitoring report presents a summary of the monitoring data used in support of the 2011 ESC (LLW Repository Ltd 2011d). The data are principally used for the development of the hydrogeological model, assessment of near field evolution, monitoring of coastal processes and monitoring of discharges from the LLWR. Further details are given in Baker and Cummings (2012) in response to a request to provide further information on the use of monitoring to reduce uncertainties (ESC-RO-SUE-007).

Our review of the 2011 ESC included the extent and appropriateness of LLW Repository Ltd's use of monitoring data. In general, we consider that that the company appropriately uses site-derived environmental monitoring and sampling data to inform the conceptualisation and assessment of the environmental pathways assessed in the 2011 ESC. For example, LLW Repository Ltd uses monitoring data to identify the nature and extent of changes in radioactive discharges from the trenches and identify trends. However, in certain areas the use of monitoring data is not as comprehensive as it could be. We would like to see an increased use of monitoring data to support model parameterisation and validation where practical and beneficial to do so, for example use of trench leachate data and container corrosion rates. Although we consider the data used in the 2011 ESC to be adequate given, for example, other conservatisms applied to assessments, we also consider that further use of monitoring data should be considered in a number of areas as the ESC is further developed. For example:

- greater use of measured parameters (for example HER, cap infiltration rates) in the calibration of groundwater flow models
- further consideration of how tritium monitoring data may be used to inform and increase confidence in groundwater flow models, particularly in the short-term. For example, particle flow lines presented in Hartley et al. (2011a) are a poor fit to the observed tritium plume[16]
- collection of site-specific biosphere data that reflect conditions local to the LLWR
- consideration of how improved monitoring of the trenches could support the ESC (see ESC-FI-023)
- improved monitoring of trench leachates for non-radiological contaminants to aid in the identification of materials that may not have been accurately declared within the past inventory
- further characterisation of landfill gas production
- further collection of monitoring data (for example container corrosion rate) to support elicited data

In future updates of the ESC, we would like to see use of site-derived monitoring information wherever practicable and beneficial in the development and calibration of conceptual and assessment models and to inform site understanding (**Recommendation SUE54**).

[16] We recognise there are practical limitations associated with the use of the tritium plume for model calibration, such as limited information on the source term.

2.4.15. Reduction in site understanding uncertainty

A robust and comprehensive environmental sampling and monitoring programme will be required to support both the forward development of the ESC and to address the inherent uncertainties associated with site understanding throughout the period of authorisation. One of the main objectives of the monitoring programme is to inform future modelling and reduce uncertainties associated with it.

In ESC-RO-SUE-007, we noted that the proposed forward monitoring programme appeared to be focused on the provision of performance assurance, rather than the systematic reduction of identified environmental uncertainties. In response to the RO, LLW Repository Ltd provided examples of potential approaches to reducing some of the 'key' uncertainties in the 2011 ESC (Baker and Cummings 2012). We define a key uncertainty as an uncertainty that has, or could have, a significant effect on the ESC. We consider that this report only partially addressed our query as it did not specifically address how the key uncertainties will be reduced to produce a more realistic assessment.

We acknowledge that assessment models are simplified and often cautious representations of real systems. Although we accept that there may be limited opportunities to reduce uncertainties in assessment model parameters through monitoring, as opposed to conceptual model uncertainties or for general confidence building, we consider that LLW Repository Ltd could make further use of monitoring data to reduce key uncertainties. This is addressed in ESC-FI-005, in which we request more information about how the company intends to develop the forward monitoring programme to address key uncertainties in the ESC, including site understanding. We expect the company to make sure that activities in this monitoring programme are clearly mapped to entries in the FEP and uncertainty tracking system to maintain the audit trail (see also ESC-FI-008).

To support the reduction of site understanding uncertainties we have asked LLW Repository Ltd to collate and integrate monitoring objectives, strategies and procedures in a single document to provide evidence of how the forward monitoring programme will be both implemented and developed throughout the period of authorisation and linked to the ESC to reduce uncertainties (ESC-FI-005).

In response to a request for further information about the forward programme (ESC-RO-SCM-005), LLW Repository Ltd identified a number of areas of further work including a review of post data freeze geological data and updating the 3-D geological model, a review of the need for tracer tests and the maintenance of geological understanding (Cumming 2011 and Peachey and Shevelan 2012). We welcome the company's commitment to improve site understanding and expect this further work to inform future ESCs.

We note there remains uncertainty associated with the nature and extent of current interactions between shallow groundwater and trench leachate. We acknowledge that the detailed monitoring of these interactions is limited by the lack of installations in and around the trench disposals, but consider it important that the predicted drying of the waste after the placement of the final cap is supported with improved site-derived evidence. An outcome of the leachate management strategy, as discussed in Sections 2.4.5 and 2.4.6 and in ESC-FI-023, should be a programme for continued monitoring and characterisation of the interactions happening between the trench leachate and the adjacent shallow groundwater. These outcomes should be used to inform site understanding and reduce uncertainty associated with the post capping behaviour of the trench disposals.

In our review of the 2002 IAF (BIO_001.1) we identified the need for ongoing improvements in the characterisation of the biosphere. These improvements would support the developing ESC and assist in reducing site understanding uncertainty. The required information can be derived from the ongoing collection of site-specific biosphere data reflecting conditions local to the LLWR. We consider that the current site environmental monitoring programme is capable of providing this information.

2.4.16. Monitoring strategy

The 2011 ESC includes a review of the long-term environmental monitoring strategy for the LLWR (Hayes et al. 2011). This review considered national and international guidance on the basis for monitoring and also identified LLWR specific requirements. The long-term monitoring strategy was

used by LLW Repository Ltd to help define current and future monitoring needs for the site, together with the purpose of that monitoring and how it may change as the site moves towards the closure and institutional control phases.

The Level 2 monitoring report describes the current environmental monitoring programme and recent underpinning sampling used to develop the 2011 ESC (LLW Repository Ltd 2011d). The report states 'we do not think it is appropriate to set out at this stage detailed proposals for monitoring over the whole period of institutional control. Rather, our approach is to demonstrate an understanding of the issue'.

Although we agree that it may not be appropriate to set out detailed proposals for monitoring over the whole period of institutional control at this stage, we do consider it important to set out a higher level monitoring strategy with objectives addressing this whole period of institutional control. In ESC-RO-SUE-008 we sought clarification of the companies approach to and mechanism for the identification of long-term monitoring objectives. We confirmed that the strategy and objectives do not need to be detailed, but at a strategic level should identify what monitoring is expected to be necessary to support the ongoing development of the ESC through to site closure and beyond and importantly to inform the need for and design of monitoring infrastructure and capability. The response provided by the company (Shevelan 2013b) described how the strategic approach will help avoid the risk of foreclosing options for collecting necessary or valuable data through progressing construction. We consider that the information provided within the 2011 ESC and in response to ESC-RO-SUE-008 provides an appropriate framework and overview of the companies approach to monitoring strategy. We recommend that LLW Repository Ltd considers how monitoring requirements and priorities will change during the period of authorisation, ensuring that no actions are taken (for example, relating to site engineering) that would unnecessarily jeopardise future monitoring opportunities (**Recommendation SUE55**).

We consider the 2011 ESC therefore meets the current needs for monitoring and we recognise that it also commits to continuing to ensure that necessary monitoring is undertaken to inform the understanding of the site and the ESC. However, we also consider that a more robust forward monitoring strategy could be developed and we detailed our expectations in ESC-FI-005.

The strategy should seek to:

- provide an effective link between the current ESC and long-term monitoring requirements
- outline how long-term monitoring needs will be reviewed and modified during site development
- provide an effective linkage between the ESC forward programme and the long-term monitoring programme
- help to identify any R&D needs
- allow the gathering of appropriate information to support the eventual surrender of the environmental permit

Hayes et al. (2011) makes a number of monitoring recommendations for the long-term and it does not appear that these have yet all been fully addressed by either taking them forward, or by providing justification for not adopting them. In addition, a recommendation by Hayes et al. (2011) on monitoring of tidal height closer to the site than Workington (the nearest tidal gauge to the LLWR) is dismissed by LLW Repository Ltd (2012a) without reference to the long-term environmental monitoring strategy. Furthermore, we identified a few minor areas of divergence between the strategy presented in Hayes et al. (2011) and the 2011 ESC, for example relating to the monitoring of carbon monoxide and hydrogen sulphide gases in the trench probes. We recommend that LLW Repository Ltd reviews the strategy presented in Hayes et al. (2011) to make sure that its recommendations have been appropriately considered (**Recommendation SUE56**).

After submission of the 2011 ESC, LLW Repository Ltd reviewed its environmental monitoring programme. In this review, the company sought to allocate a clear monitoring or sampling objective to all aspects of its environmental monitoring programme (LLW Repository Ltd 2012a). This process has brought about an improved understanding of the monitoring information collected from across the LLWR and allowed monitoring requirements to be better linked to ESC requirements.

3. Meeting our requirements

LLW Repository Ltd submitted the 2011 ESC against Schedule 9 Requirement 6 of the current LLWR environmental permit (Environment Agency 2010). This required LLW Repository Ltd to 'update the Environmental Safety Case(s) for the site covering the period up to withdrawal of control and thereafter'.

We define an ESC as, 'the collection of arguments, provided by the developer or operator of a disposal facility that seeks to demonstrate that the required standard of environmental safety is achieved' (Environment Agency et al. 2009). In this section we provide a summary of our review of the site understanding, site evolution and monitoring sections of the 2011 ESC and assess whether relevant parts of the GRA are met.

This report specifically covers how the ESC addresses the following requirements within the GRA:

- Requirement R9: Environmental radioactivity
- Requirement R11: Site investigation
- Requirement R14: Monitoring
- Requirement R10: Protection against non-radiological hazards

It also addresses other broader areas of the GRA. Each of these requirements and other areas are discussed below in relation to the extent that the 2011 ESC meets the expectations of the GRA and also Schedule 9 Requirement 6 of the environmental permit.

The ESC should describe 'all aspects that may affect environmental safety, including geology, hydrogeology and surface environment of the site' (GRA paragraph 7.2.6). No specific guidance is provided for the characterisation of a near-surface repository and its environs, or the determination of a long-term evolution sequence culminating in coastal disruption. However, the GRA specifies a number of generic principles that should be applied during the site characterisation and monitoring processes, including:

- the development of a clear understanding of the evolution of the site
- the generation and use of scientific information and use of expert judgement
- the management of uncertainty

In our review, we have sought to determine whether LLW Repository Ltd has demonstrated an appropriate understanding of the site and its environs and its likely long-term evolution. We have also considered whether the existing monitoring arrangements are suitable for demonstrating environmental safety as well as reducing uncertainties in the ESC.

3.1. Requirement R9: Environmental radioactivity

Requirement R9 of the GRA states, 'The developer/operator should carry out an assessment to investigate the radiological effects of a disposal facility on the accessible environment both during the period of authorisation and afterwards with a view to showing that all aspects of the accessible environment are adequately protected' (GRA Paragraph 6.3.70).

We are satisfied that LLW Repository Ltd has the necessary monitoring provisions in place to support the subsequent assessment of discharges to the environment. The monitoring provision appropriately reflects the current stage of development of the repository. We consider that this requirement has been met.

3.2. Requirement R11: Site investigation

Requirement R11 of the GRA states ‘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' (GRA Paragraph 6.4.6).

We are satisfied that LLW Repository Ltd has appropriately characterised the LLWR and its setting using both on-site and, to a lesser extent, off-site geological and hydrogeological information from multiple investigations. The heterogeneous nature of the Quaternary deposits underlying the LLWR means that precise characterisation of the layout of low and high permeability lithologies may not be achievable. We consider that the geological interpretation and resultant modelling of the Quaternary geologies is appropriate, however, there will always remain a significant level of uncertainty over the behaviour of groundwater within these geologies at a small scale (10s to 100 metres). Because of this complexity, further site investigation may not significantly reduce geological uncertainty. With the exception of the land between the site and the coastline where there are practical access constraints, we consider that the LLWR and its environs have been adequately investigated to be able to support the 2011 ESC.

We expect future site investigation information to continue to inform the LLWR design and future monitoring programme and support the conceptualisation of the site. In addition to the provision of a forward programme designed to investigate significant uncertainties and align with the outputs of the 2011 ESC, we expect future site investigation to be carried out on an opportunistic basis and to support the construction of future vaults.

LLW Repository Ltd has used an iterative approach to the development of geological and hydrogeological conceptual models and the groundwater flow model. The company does not provide detailed proposals for updating these models in the forward programme. We expect LLW Repository Ltd to continue to iterate and develop the current geological and hydrogeological models to support future updates to the ESC. Where appropriate the forward programme should be supported with site characterisation information. We set out our requirements for a forward programme in ESC-FI-004.

The conceptualisation of the site used to build the 2011 ESC drew on an appropriate range of site-derived information. As the ESC becomes more established and more site performance information becomes available we expect to see an increase in the use of site-derived information together with continued alignment of the site monitoring programme with the information needs of the ESC.

Site investigation information also formed an important element of the provision of the coastal studies programme that covers conceptualisation and characterisation of the coastal landscape and coastal processes affecting the evolution of the coastline. This aspect of the site investigation programme is less established than that used to inform the groundwater pathway assessment. We expect LLW Repository Ltd to continue to collect and use site investigation data to enhance understanding of future coastal change.

We consider that LLW Repository Ltd has appropriately used geological, hydrogeological and geotechnical data to inform the engineering concept and design. However, the conceptual nature of the engineering design means that the design has not yet been fully developed in detail. As future vaults are constructed site investigation data will be needed to inform the design. As the design is developed further we also expect to see greater use of site-derived information to support the engineering performance assessment and substantiate the projected long-term behaviour and performance of engineered systems and geological barriers.

We conclude that LLW Repository Ltd has appropriately used information gained from site investigation to inform the geological and hydrogeological conceptualisation of the LLWR and its environs, support the projections of coastal erosion and to inform the engineering concept and design. We consider that the company has adequately addressed Requirement R11 at this point in time, although we put forward several recommendations that the company should address to make sure that it continues to meet this requirement in the future.

3.3. Requirement R14: Monitoring

Requirement R14 of the GRA states, ‘the developer/operator of a disposal facility for solid radioactive waste should carry out a programme to monitor for changes caused by the construction, operation and closure of the facility’ (GRA Paragraph 6.4.31).

LLW Repository Ltd has a substantial programme of monitoring that covers both environmental monitoring, for example discharges and hydrogeological parameters, and performance of engineered barriers. The monitoring is done for a variety of reasons, including:

- to demonstrate compliance with the environmental permit
- to develop baseline conditions
- to demonstrate that the site is not giving rise to unacceptable environmental hazards
- to demonstrate that the performance of the facility is consistent with assumptions in the ESC
- to address significant uncertainties

This programme has been refined over the years of operation to meet the changing needs of the LLWR as it has been developed and the changing regulatory requirements. We reviewed the development of the environmental monitoring programme as part of our routine regulatory activities.

We consider that the current monitoring programme is appropriately aligned with environmental pathways and receptors and is carried out within a comprehensive quality framework. LLW Repository Ltd has mechanisms in place to make sure that the outcomes of the monitoring programme are reviewed in a timely manner, any action is taken if necessary and, if required, future updates of the ESC are informed. Thus, we are satisfied that the LLWR environmental monitoring programme is capable of providing appropriate information to allow ongoing assessment of the repository's performance. We will continue to review the monitoring program and its linkage to the ESC as part of our routine regulatory activities.

As part of the current environmental permit, LLW Repository Ltd has submitted annual reports describing the extent and outputs of the environmental monitoring programme and the performance of the trench disposal cut-off wall and capping system. These reports are able to demonstrate ongoing LLWR performance and inform the 2011 ESC. We have recommended that regular reporting of environmental performance and trench engineering performance is continued.

Future monitoring at the LLWR will play an important role in increasing understanding and reducing uncertainties in a number of important areas within the ESC, including:

- characterisation of trench leachate, in particular to determine the presence of complexants and colloids and better understand the non-radioactive component of the leachate
- evolution of the near field and supporting the further development of the near field models
- groundwater flow and contaminant migration, in particular related to impacts of small-scale variability in geological properties, better definition of contaminant migration pathways and validation of groundwater flow models
- the nature and extent of cap settlement
- evolution of the coastline
- performance of components of the engineered barrier system

LLW Repository Ltd presents the current environmental monitoring programme (LLW Repository Ltd 2011d) together with a long-term monitoring strategy covering the period of authorisation (Hayes et al. 2011) in the 2011 ESC. Although the proposals put forward in the long-term monitoring strategy seem reasonable, we consider that the main body of the 2011 ESC has not fully taken account of them. Subsequent to issue of the 2011 ESC, the company has carried out further work to identify monitoring objectives and align the monitoring strategy with the ESC. We require the company to collate and integrate monitoring objectives, strategies and procedures in a single document so as to provide evidence of how the forward monitoring programme will be implemented and developed throughout the period of authorisation and linked to the ESC in order to reduce uncertainties (ESC-FI-005). In this FI we also ask the company to further reduce ESC uncertainties using monitoring where possible. We have raised further FIs on future monitoring requirements in some significant areas, including targeted monitoring of the tritium plume in groundwater (ESC-FI-002), non-radiological contaminant concentrations (ESC-FI-006), colloids (ESC-FI-015) and complexants (ESC-FI-009) in the near field, coastal erosion over the long-term

(ESC-FI-019) and performance of the engineered systems (ESC-FI-001 and ESC-FI-23 to ESC-FI-27).

The ESC needs to show how the various components of the disposal system contribute to ensuring environmental safety. We consider that the environmental monitoring programme, although adequate, could be more closely aligned with this objective to demonstrate the performance of individual components of the disposal system, for example leachate and gas monitoring strategies, as well as the performance of the overall facility. We recognise that at this stage of the development of the LLWR many aspects of repository performance will be based on the outputs of models and expert elicitation. As the LLWR is further developed we will expect the environmental monitoring programme to be able to collect relevant environmental monitoring information to inform future updates of the ESC.

In summary, we consider that LLW Repository Ltd has designed and implemented a comprehensive environmental monitoring programme capable of demonstrating compliance with authorised discharge limits and assurance of radiological protection of members of the public during the period of authorisation. We believe that this programme is appropriate for demonstrating the LLWR is capable of operating within the parameters set out in the 2011 ESC. We therefore consider that the company has adequately addressed Requirement R14 of the GRA at this point in time, although we have put forward a number of recommendations and FIs that it should address to make sure that it continues to meet this requirement and to further improve the monitoring carried out (Environment Agency 2015g).

3.4. Requirement R10: Protection against non-radiological hazards

Requirement R10 of the GRA states, 'the developer/operator of a disposal facility for solid radioactive waste should demonstrate that the disposal system provides adequate protection against non-radiological hazards' (GRA Paragraph 6.4.1).

LLW Repository Ltd carries out a monitoring programme for non-radioactive contaminants in leachate, groundwater and surface water. Data from this programme have been used to inform the non-radiological groundwater assessment. We consider this programme adequate to support the needs of the GRA, but with scope for further improvement. We have identified possible further improvements to the non-radioactive component of the monitoring programme to better align with that of a conventional (non-radioactive waste) landfill and we have raised an FI (ESC-FI-006) that sets out our requirements for improvements (Environment Agency 2015g).

3.5. Other requirements of the GRA

This report has addressed a number of other broader areas that are not necessarily directly related to a specific GRA requirement, but which, are all relevant to the production of an ESC. Some of these issues are summarised below.

Based on the GRA requirement to demonstrate passive safety and no reliance on human action (Principle 4: reliance on human action), the 2011 ESC site evolution investigation is built on the assumption that no active engineering measures, such as coastal defences, will be deployed after the end of the period of authorisation.

LLW Repository Ltd uses expert judgement to inform its projections of site evolution and coastal erosion. We consider this appropriate. We expect these predictions to be reviewed as climate change science develops.

We consider that LLW Repository Ltd has appropriately used site-derived information to develop a robust understanding of the performance of the LLWR and underpin the 2011 ESC. We further consider that the site conceptualisation and projected evolution sequence has been appropriately incorporated into the 2011 ESC assessment scenarios.

Destruction of the LLWR by coastal erosion is presented as the most likely endpoint for the site in the 2011 ESC. We agree that the information presented in the 2011 ESC is sufficiently robust and comprehensive to support this assumption. We consider that LLW Repository Ltd has assessed a sufficient range of alternative variant scenarios to understand the significance of differing factors controlling the timing and nature of site disruption. We recognise that, because of the complex

nature of external climate change factors and the response of the coastal environment to climate change, uncertainty is likely to remain high.

3.6. Summary

We consider that LLW Repository Ltd has adequately addressed the parts of the GRA relevant to site understanding and evolution. The company has demonstrated an adequate understanding of the current and future repository environmental setting and evolution sequence that has been used to inform the development of the 2011 ESC.

4. Conclusions

LLW Repository Ltd submitted the 2011 ESC against Schedule 9 Requirement 6 of the current LLWR environmental permit. We consider that in the 2011 ESC, LLW Repository Ltd demonstrates an adequate understanding of the site setting and the evolution of the LLWR.

The 2011 ESC has been effectively informed by a comprehensive and high quality monitoring programme. LLW Repository Ltd has also recognised the need for a wide ranging future monitoring programme, encompassing a wide range of environmental media throughout the period of authorisation. We consider that current monitoring and the future monitoring proposals are sufficient for the purposes of demonstrating environmental safety and continued maintenance of the ESC.

The overall quality of the 2011 ESC submission in the area of site understanding, evolution and monitoring is high, with information based on a comprehensive site investigation programme and sound science. The clarity of the safety arguments is generally good and the supporting information can generally be traced back to the source documents. However, the level of detail in the Level 1 and 2 documents, taken in isolation, was insufficient to allow us to assess the 2011 ESC arguments properly. We had to review Level 3 documents and request further documents not included in the original 2011 ESC submission to obtain enough information for our review.

This notwithstanding, we identified a number of areas for improvement in the future, as highlighted in this document. These areas are outlined in our recommendations and forward issues. We will require LLW Repository Ltd to demonstrate progress against them.

We consider that LLW Repository Ltd has adequately addressed the parts of the GRA relevant to site understanding, evolution and monitoring. The company has demonstrated an adequate understanding of the current and future LLWR environmental setting and evolution sequence that has been used to inform the development of the 2011 ESC.

The 2011 ESC presents the outcome of an extensive site investigation and interpretation programme. This programme has provided a level of site understanding sufficient to support the 2011 ESC assessments.

The information collected and reviewed as part of the programme of work to inform site understanding and its evolution was designed to help conceptualise the environmental setting of the LLWR and to inform the 2011 ESC. We conclude that it has met this objective, using a scientifically robust investigation and presentation of the LLWR environmental setting throughout the required assessment period.

The 2011 ESC described the expected disruption of the LLWR by coastal erosion processes. LLW Repository Ltd has concluded that the site is almost certain to be eroded by the sea over time. The company projects that erosion of the LLWR is likely to start between a few 100 and a few 1000 years from now. It believes the vaults and trenches will be completely eroded within 1000 to a few 1000 years. We agree that these projections are reasonable and represent best available knowledge at this time. The resulting narrative and conceptualisation provides support to many high level safety arguments made throughout the 2011 ESC. We consider that these arguments have appropriately taken account of the significant uncertainty associated with both the site disruption mechanisms and the timing of the site disruption.

Overall, regarding the topic areas addressed in this report, we consider that LLW Repository Ltd has met the requirements of the GRA and Schedule 9 Requirement 6 of the current LLWR environmental permit through the 2011 ESC and supporting documents. This evidence is of a suitable standard and quality to support an environmental permit decision on future disposals at the site.

5. References

Arup Geotechnics, 2000. Drigg Capping and Drainage Study. DTP/06.

Baker, A., 2012. Technical Memorandum: Gas Generation Rate Plots from GRM Calculations. LLW Repository Ltd Report LLWR06488/06/10/01.

Baker, A., 2013. Response to Issue Resolution Form ESC-TQ-SUE-010 (Uncertainty Associated with Isostatic Changes at the LLWR). LLW Repository Ltd ESC Technical Memo LLWR/ESC/Mem(13)195.

Baker, A. J. and Cummings, R., 2012. Response to Issue Resolution Form ESC-RO-SUE-007 (Use of Future Monitoring to Reduce Uncertainties). LLW Repository Ltd ESC Technical Memo LLWR/ESC/Mem(12)176.

BIOCLIM, 2004, Deliverable D10-12: Development and Application of a Methodology for taking Climate-driven Environmental Change into account in Performance Assessments, ANDRA, Parc de la Croix Blanche, 1/7 rue Jean Monnet, 92298 Châtenay-Malabry, France.

BNFL, 2002a. Drigg Post-Closure Safety Case: Overview Report, British Nuclear Fuels plc.

BNFL, 2002b. Drigg Operational Environmental Safety Case, British Nuclear Fuels plc.

BNFL 2002c. Drigg Post-Closure Safety Case: Far-field Geochemical Interpretation Report.

BNFL, 2007. 2007 Annual Performance Assessment of the Interim Cap and Cut-off Wall at the LLWR Trenches. BNFL Report 51905150-002-181-Rep-002-A3.

Carson, P., 2010. Examination of International Radioisotope Assay Practice. LLW Repository Ltd Report LLWRESC/R(10)10015 Issue 1.

CIRIA, 2013. Guidance on the Management of Landfill Sites and Land Contamination on Eroding or Low-lying Coastlines. CIRIA Report C718.

Clarke, R., 2011. Joint Environment Agency & ONR Inspection of Environmental Monitoring and Contaminated Land Arrangements. Letter from R. Clarke of the Environment Agency to S. Hunter of LLW Repository Ltd, reference OTH/11/328.

Cummings, R., 2011. ESC Forward Programme. LLW Repository Ltd Report LLWR/ESC/R(11)10040.

Department for Communities and Local Government, 2012. National Planning Policy Framework.

Eden, L. and Barber, N., 2007. Assessment of the Impact of Radioactive Disposals and Discharges at the LLWR on the Ecosystem. Nexia Solutions Report (07) 8310: Issue 3.

Environment Agency, Northern Ireland Environment Agency and Scottish Environment Protection Agency, 2009. Near-Surface Disposal Facilities on Land for Solid Radioactive Waste: Guidance on Requirements for Authorisation, February 2009.

Environment Agency, 2005. The Environment Agency's Assessment of BNFL's 2002 Environmental Safety Cases for the Low-Level Radioactive Waste Repository at Drigg, NWAT/Drigg/05/001, Version: 1.0.

Environment Agency, 2009a. Review of LLW Repository Ltd's "Requirement 2" submission, Overview.

Environment Agency, 2009b. Review of LLW Repository Ltd's "Requirement 2" submission, Technical Review of Volume 4: Site Understanding.

Environment Agency 2009c. Environment Agency Compilation Of Environment Agency Requirements, Etc. Made Under Authorisation Number BZ2508/BZ2508 Issued to British Nuclear Group Sellafield Ltd. for the Disposal Of Radioactive Waste from the Low Level Waste Repository, Drigg, Cumbria.

Environment Agency, 2010.The Environmental Permitting (England and Wales) Regulations 2010, Permit Number EPR/YP3293SA, 21 December 2010.

Environment Agency, 2011a, RASCAR Inspection Form, Environmental Monitoring & Contaminated Land Arrangement, I/090311/YP3293SA & I/140311/YP3293SA, 9th, 14th and 15th March 2011.

Environment Agency, 2011b. Horizontal Guidance Note H1 - Annex J 3. Additional Guidance for Hydrogeological Risk Assessments for Landfills and the Derivation of Groundwater Control Levels and Compliance Limits. Environment Agency Report GEHO0212BULU-E-E, Version 2.

Environment Agency, 2014a. Form HR02: Pro forma for stage 3 Appropriate Assessment, Drigg Low Level Waste Repository, Environmental Permit Variation EPR/YP3293SA/V002, July updated October 2014.

Environment Agency, 2014b. Further information notice to support variation application EPR/YP3293SA/V002, 21 May 2014.

Environment Agency, 2015a. Review of LLW Repository Ltd's 2011 Environmental Safety Case: Overview Report, Issue 1.

Environment Agency, 2015b. Review of LLW Repository Ltd's 2011 Environmental Safety Case: Safety Case Management, Issue 1.

Environment Agency, 2015c. Review of LLW Repository Ltd's 2011 Environmental Safety Case: Inventory and Near-field, Issue 1.

Environment Agency, 2015d. Review of LLW Repository Ltd's 2011 Environmental Safety Case: Optimisation and Engineering, Issue 1.

Environment Agency, 2015e. Review of LLW Repository Ltd's 2011 Environmental Safety Case: Assessments, Issue 1.

Environment Agency, 2015f. Review of LLW Repository Ltd's 2011 Environmental Safety Case: Issues Resolution Forms, Issue 1.

Environment Agency, 2015g. Review of LLW Repository Ltd's 2011 Environmental Safety Case: Forward Issues, Issue 1.

Environment Agency, 2015h. Review of LLW Repository Ltd's 2011 Environmental Safety Case: Issues Assessment Forms, Issue 1.

Environment Agency, 2015i. Review of LLW Repository Ltd's 2011 Environmental Safety Case: Non-technical summary, Issue 1.

Environment Agency, 2014. Environment Agency National Coastal Erosion Map. http://apps.environment-agency.gov.uk/wiyby/134831.aspx [Accessed 10 December 2014].

Environment Agency, Northern Ireland Environment Agency and Scottish Environment Protection Agency, 2009. Near-Surface Disposal Facilities on Land for Solid Radioactive Waste: Guidance on Requirements for Authorisation.

Fairhurst, A., 2013. Audit of 2011 ESC Groundwater Pathway Calculations. Letter from A. Fairhurst of the Environment Agency to R. Cummings of LLW Repository Ltd, reference LLWR/13/015/O. 8 November 2013.

Fish P., Thorne M., Moore R., Penfold J., Richards L., Lee M. and Pethick J., 2010. Forecasting the Development of the Cumbrian Coastline in the Vicinity of the LLWR site, Quintessa Report Ref: QRS-1443X-1 Version 1.

Garrard, G., Fish, P., Towler, G. and Penfold, J., 2012. LLWR 2012 Slope Stability of the Eroding Waste Mass. LLW Repository Ltd Report QRS-1443ZO01.

Halcrow, 2010a. Low Level Waste Repository Ltd Drigg Coastal Erosion Geophysical Report. Halcrow Report 291038-001.

Halcrow, 2010b. Main SMP2 Document, Report Prepared for the North West and North Wales Coastal Group as part of the Second Round Shoreline Management Plan for Cell 11.

Halcrow, 2010c. North West & North Wales Coastal Group: North West England and North Wales Shoreline Management Plan SMP2 Main SMP2 Document.

Halcrow, 2012. Significance of the Dune System at Drigg. Halcrow Technical Note ESC-TQ-SUE-022.

Halcrow, 2013a. Technical Note: TQ response: Extreme Events, ESC-TQ-SUE-019, February 2013.

Halcrow, 2013b. Coastal inspection, 2013, Cumbria Coastal Studies.

Hartley, L., Applegate, D., Couch, M., Hoek, J., Jackson, C. P. and James, M., 2011a. Hydrogeological Modelling for LLWR 2011 ESC, Serco Report SERCO/TCS/E003632/007 Issue 3.

Hartley, L., Applegate, D., Couch, M., Jackson, C. P. and James, M., 2011b. Hydrogeological Modelling for 2011 LLWR ESC. Phase 2. Serco Report No. SERCO/TCS/E003632/005 Issue 5.

Hayes, P., Keep, M., Fretwell, B. and Smith, G., 2011. Long-term Environmental Monitoring Strategy. Entec report 27280 Issue 4.

Henderson, D. E., 2008. LLWR Lifetime Project: Estimation of LLWR Stream Baseflows and Implications for Water Balance and Recharge. Nexia Solutions Report (08)9768 Issue 1.

Henderson, D. E., 2011. Estimation of Tritium Fluxes from the LLWR – Initial Review of Data Availability. NNL Report (09)10766.

HMSO, 2010. Planning Policy Statement 25: Development and Flood Risk.

Hunter-Smith, R., 2011. 2010 Annual Perfomance Assessment of the Interim Cap and Cut-off Wall of the LLWR Trenches. LLW Repository Ltd Report RP/103547/4510034188/PROJ/0038.

IPCC, 2007. IPCC Fourth Assessment Report (AR4). Climate Change 2007: Synthesis Report. Pachauri, R.K. and Reisinger, A. (Eds.). IPCC, Geneva, Switzerland. pp 104.

IPCC, 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J.,. Nauels, A., Xia, Y., Bex, V. and Midgley, P.M. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IAEA, 2014, Modelling and Data for Radiological Impact Assessments "MODARIA" Project webpage. Available at: http://www-ns.iaea.org/projects/modaria/default.asp [Accessed November 2014].

Jackson, C. P., 2011. Hydrogeological Conceptual Model for LLWR 2011 ESC. Serco Report SERCO/TAS/003632/008 Issue 2.0.

Jackson, C. P., Couch, M., Yates, H., Smith, V., Kelly, M., James, M., 2011. Elicitation of Uncertainties for LLWR. Serco Report Serco/TAS/E003796/010 Issue 2.

Jefferies, N., 2009. Alternative Hydrogeological Models for LLWR. Serco Report SERCO/TAS/002985/001 Issue 1.

Jefferies, N., 2011. Trench Cap Cut-off Wall Performance Review Incorporating the 2011 Annual Response to Environment Agency Schedule 7 Requirement 7. LLW Repository Ltd Report RP/3409246/PROJ/00220/A, Issue 1.

Jefferies, N., 2012. LLWR, Vault 8 Containers Issues Project: Position Paper. LLW Repository Ltd Report RP/LLWRGR/PROJ/00139 ISSUE A.

Jenkins, G. J., Murphy, J. M., Sexton, D. M. H., Lowe, J. A., Jones, P. and Kilsby, C. G., 2009. UK Climate Projections: Briefing Report. Met Office Hadley Centre, Exeter, UK.

LLW Repository Ltd, 2007. LLWR Lifetime Project: 2007 Annual Response to Environment Agency's Schedule 9, Requirement 8 as part of 2006 Authorisation BZ2508/BZ2508, LTP/Sch9/Req8/07 Issue 1.

LLW Repository Ltd, 2008a. Annual Performance Assessment of the Interim Cap and Cut-off Wall at the LLWR Trenches; RP/103657/4510034188/PROJ/00002/A.

LLW Repository Ltd, 2008b. LLWR Lifetime Plan: Site Understanding, 10004 LLWR LTP, Volume 4.

LLW Repository Ltd, 2008c. LLWR Lifetime Plan. 2008 Annual Response to Environment Agency Schedule 9 Requirement 8, 10006 LLWR LTP Issue 01.

LLW Repository Ltd, 2009a. Annual Performance Assessment of the Interim Cap and Cut-off Wall at the LLWR Trenches; RP/103657/4510034188/PROJ/000019/A.

LLW Repository Ltd, 2009b. 2009 Annual response to Environment Agency Schedule 9 Requirement 8, LLWR/EA/08/0008-02, 20th April 2009.

LLW Repository Ltd, 2010a. Annual Performance Assessment of the Interim Cap and Cut-off Wall at the LLWR Trenches, RP/103547/4510034188/PROJ/00038.

LLW Repository Ltd, 2010b. Annual Response to Environment Agency Schedule 9, Requirement 8, LLWR/EA/10/0061-01.

LLW Repository Ltd, 2011a. The 2011 Environmental Safety Case. Hydrogeology. LLWR/ESC/R(11)10022.

LLW Repository Ltd, 2011b. The 2011 Environmental Safety Case. Assessment of Long-Term Radioactive Impacts. LLWR/ESC/R(11)10028.

LLW Repository Ltd, 2011c. The 2011 Environmental Safety Case. Site Evolution. LLWR/ESC/R(11)10023.

LLW Repository Ltd, 2011d. The 2011 Environmental Safety Case. Monitoring. LLWR/ESC/R(11)10024.

LLW Repository Ltd, 2011e. The 2011 Environmental Safety Case. Environmental Safety During the Period of Authorisation. LLWR/ESC/R(11)10027.

LLW Repository Ltd, 2011f. The 2011 Environmental Safety Case. Assessment of Non-Radioactive Impacts. LLWR/ESC/R(11)10029.

LLW Repository Ltd, 2011g. The 2011 Environmental Safety Case. Extended Disposal Area. LLWR/ESC/R(11)10035.

LLW Repository Ltd, 2011h. The 2011 Environmental Safety Case. Engineering Design WR/ESC/R(11)10020.

LLW Repository Ltd, 2011i. The 2011 Environmental Safety Case. Inventory. LLWR/ESC/R(11)10019.

LLW Repository Ltd, 2011j. The 2011 Environmental Safety Case. Near Field. LLWR/ESC/R(11)10021.

LLW Repository Ltd, 2012a. ESC Review of the Monitoring Programme: Post 2011 ESC, LLWR/ESC/R(12)10048, November 2012.

LLW Repository Ltd, 2012b. Assessment of Radiological Impacts in the Very Long-term if the LLWR is not Eroded. LLW Repository Ltd Report LLWR/ESC/R(12)10047 Issue 1.

LLW Repository Ltd, 2013a. 2011 Low Level Waste Repository Environmental Safety Case: Features, Events and Processes and Uncertainty Tracking System.LLW Repository Ltd Excel Spreadsheet MASTER 2011 FEP List_LLWR04127061103_0_2 - ajb7 macro Jan 2013.

LLW Repository Ltd, 2013b. Trench Cap and Cut-off Wall Performance Review Incorporating the 2012 Annual Response to Environment Agency Schedule 9 Requirement 7, RP/LLWRGR/PROJ/00148/A.

LLW Repository Ltd, 2013c. Developments Since the 2011 ESC. LLW Repository Ltd report LLWR/ESC/R(13)10058, Issue 1.

LLW Repository Ltd, 2013d. Environmental Monitoring Review Report 2012. RP/LLWRGR/PROJ/00144/B, April 2013.

LLW Repository Ltd, 2013e. Application to Vary LLWR's Permit. LLWR/ESC-R(13)10057 Issue 1.

Michie, U., Hunter, J. and Towler, G., 2010. LLWR ESC: The Geology of the LLWR Site and Surrounding Region, Quintessa report QRS-1443Y-R1 Version 2.

NNL, 2009. Cumbria Coastal Studies – Coastal Monitoring Results and Analysis – June 2009. NNL Report (08)10507 Issue 0.1a.

Peachey, J. And Shevelan, J., 2012. ESC Review of the monitoring programme: Post 2011. LLWR/SC/R(12)10048. November 2012.

Royal Haskoning, 2010. Soft Cliff And Platform Erosion (SCAPE) Modelling of the Drigg Coast. Draft report to LLW Repository Ltd.

Serco, 2010. ESC-LLWR Environmental Monitoring Review Report 2009, LLWR Report 9020/4510257854. April 2010.

Serco, 2011a. Trench Cap and Cut-off Wall Performance Review Incorporating the 2011 Annual Response to Environment Agency Schedule 9 Requirement 7, LLWR Report RP/3409246/PROJ/00220/A.

Serco, 2011b. 2011 Annual Response to Environment Agency Schedule 9 Requirement 8, Serco/E005170/001 Issue 1.

Serco, 2012. 2012 Annual Response to Environment Agency Schedule 9 Requirement 8, Serco/E00680/001 Issue 1.

Shaw, N., 2013. Engineering Forward Plan to Support the Environmental Safety Case. LLW Repository Ltd Report RP/LLWRGR/PROJ/00142 Issue A, April 2013.

Shevelan, J., 2011. 2010 Review of Leachate, Groundwater and Surface Water Monitoring. LLW Repository Ltd Report RP/DR-GEN/PROJ/00035 Issue 2.0.

Shevelan, J., 2013a. Assessment Code Documentation and Quality Assurance, LLW Repository Ltd ESC Technical Memo LLWR/ESC/MeM(13)206.

Shevelan, J., 2013b. ESC Technical Memo: Long-term monitoring. LLWR/ESC/MeM(13)200.

Smith, N., 2009. Interpretation of Geology Exposed in Vault 9 Excavation and Integration with Other Geological Information. NNL Report (08)10176. Issue 0.1.

Smith, N., 2011. 3D Geological Modelling to Support 2011 ESC, NNL Report (10) 11217 Issue 4.

Speed, C. and Fretwell, B., 2010. A Report on the Hydrogeochemistry of Non-Radioactive Contaminants in LLWR Leachate and Groundwater. Entec Report 27635.

Sumerling, T., 2012. Timing of Disruption of the LLWR by Coastal Erosion. LLW Repository Ltd ESC Project Memo LLWR/ESC/Mem(12)158.

Thorne, M. C., 2008. LLWR Lifetime Project: Estimates of Cap Infiltration and Erosion, Nexia Solutions Report (08) 9274 Issue 2.

Thorne, M. C., 2009. LLWR Lifetime Project: R&D on Climate Change and Site Evolution. National Nuclear Laboratory Report NNL 10509, Issue 3.

Thorne, M. C. and Schneider, S., 2011. Assessment of the Impacts on Non-human Biota for the LLWR 2011 ESC. Serco Report SERCO/TCS/00435/01 Issue 2.

Towler, G., Black, J. and Bond, A. E., 2007. LLWR Lifetime Project: Reassessment of the LLWR Site Water Balance. Quintessa Report QRS-1354F-LLWRWBV1.1. Nexia Solutions Report (07)8507.

URS, 2009. Installation of Stage 6 (Offsite) Boreholes. Factual Report. Issue No 2. URS Report 49308240.

Walkden, M. J. A. and Hall, J. W., 2005. A Predictive Mesoscale Model of the Erosion and Profile Development of Soft Rock Shores. Coastal Engineering 52, 535–563.

Woollard, H. and Jackson, C. P., 2012. The Effects of Faults on the Hydrogeology at the LLWR Serco Report SERCO/TAS/005864 Issue 1.

6. Appendix 1 - Issue Resolution Forms

6.1. Introduction

As outlined in Section 1.3, Issue Resolution Forms (IRFs) are detailed records of concerns and queries raised as part of our review of the ESC. Each IRF includes one or more actions. LLW Repository Ltd was required to provide a substantive response to the action(s) specified on the IRF by the specified date(s). Issues were closed out only when we had determined that the LLW Repository Ltd response adequately addresses the issue.

6.2. Site understanding and evolution Issue Resolution Forms

Summaries of Regulatory Observations (ROs) and Technical Queries (TQs) raised during our review of the 2011 ESC site understanding review work are reproduced in Table 1 and Table 2 respectively. No Regulatory Issues (RIs) were raised in this area. These IRFs are reproduced in full in Environment Agency (2015f). The IRFs are not sequentially numbered. This is because some IRFs were identified as possible queries but not issued, for example, following further detailed review of information provided in support of the 2011 ESC, or following on from clarifications provided by LLW Repository Ltd. All IRFs have now been closed.

It should be noted that a number of IRFs have been classified under the site understanding and evolution (SUE) subject area but also relate to the engineering and optimisation report (Environment Agency 2015d).

Table 1 Regulatory Observations

Regulatory Issue number	Title	Summary
ESC-RO-SUE-007	The use of future monitoring to reduce uncertainties in the ESC	We asked LLW Repository Ltd to provide evidence of how the forward monitoring programme will be developed throughout the period of authorisation and linked to the ESC to reduce key uncertainties.
ESC-RO-SUE-008	Development of a long-term monitoring strategy to support the ESC	We asked LLW Repository Ltd to describe its approach to and mechanism for, the identification of long-term monitoring objectives and the incorporation of these objectives into the ESC.

Table 2 Technical Queries

Regulatory Issue number	Title	Summary
ESC-TQ-SUE-010	Isostasy monitoring	We asked LLW Repository Ltd to assess the viability, usefulness and practicality of taking site-derived isostasy measurements of relative ground height, at a useful accuracy, over an extended timeframe.
ESC-TQ-SUE-011	Slope stability assessment of the eroding waste mass	We sought an improved description of the geotechnical properties of the waste and LLWR engineering systems as their composition may influence coastal erosion and the stability of the eroding waste mass.

Regulatory Issue number	Title	Summary
ESC-TQ-SUE-019	Extreme events	We asked LLW Repository Ltd to clarify the role of extreme events such as storm surges on the modelled site disruption sequence.
ESC-TQ-SUE-022	Understanding the role of the dune system	We asked LLW Repository Ltd to clarify the evolution sequence and role of the Drigg dune systems in the predicted coastal evolution sequence.
ESC-TQ-SUE-025	Understanding coastal recession	We asked LLW Repository Ltd to justify why 1000 years was selected as an appropriate reference time for coastal recession to reach the disposal area site boundary.

7. Appendix 2 - Recommendations

7.1. Introduction

Recommendations raised as a result of our review of the 2011 ESC represent areas where we see scope for possible improvement or development, but which are relatively minor in nature relative to FIs. As a matter of good practice we expect LLW Repository Ltd to address these recommendations and will expect a mechanism to be put in place to track them.

7.2. Site understanding and evolution recommendations

Table 3 summarises the recommendations made in this report. Further details are provided in Section 2.

Table 3 Site understanding and evolution recommendations

Recommendation number	Summary of recommendation
SUE 1	LLW Repository Ltd should continue to review the quality and appropriateness of past borehole data and make sure it is appropriately used to inform future ESCs.
SUE2	As understanding and technology related to geophysical surveying increases, we expect LLW Repository Ltd to take this into account and to undertake further geophysical surveys or reprocess existing information as appropriate, to further inform site geological understanding.
SUE3	LLW Repository Ltd should seek to undertake further opportunistic investigations of the area between the LLWR and the coast, taking into account access constraints and without compromising the integrity of the protected environment. This might, for example, include re-assessment of existing information and the construction of boreholes immediately adjacent to, but not within, the protected sites.
SUE4	In future updates of the ESC, we expect to see clear identification of models being used and demonstration that they have clear audit trails.
SUE5	We recommend that any observed or predicted changes in the nature and extent of the dunes is considered in future reviews of the ESC hydrogeological models.
SUE6	As the shoreline is eroded, we recommend that geological information derived from the exposed cliffs is considered in the repository geological model where appropriate.
SUE7	LLW Repository Ltd should include where possible the reduction of the remaining uncertainties in the repository conceptualisation as a site investigation objective.
SUE8	LLW Repository Ltd should further investigate the potential effect of incised infilled channels acting as fast groundwater pathways.
SUE9	LLW Repository Ltd should continue to review the importance of contaminant migration in the upper sandstone. This should include consideration of the relative importance of fracture

Recommendation number	Summary of recommendation
	flow versus matrix flow in the upper sandstone, as well as the potential effect of faults on flow within the upper sandstone.
SUE10	We recommend that applicable outcomes from the groundwater mound investigations should be considered in future updates of the ESC. If the groundwater mound is found to be the result of measurement errors, then we would expect the site hydrogeological understanding to be updated accordingly.
SUE11	LLW Repository Ltd should monitor the effects of the construction of future vaults on contaminant migration and the behaviour of the existing trench contamination plume throughout the construction and restoration sequence.
SUE12	LLW Repository Ltd should consider potential improvements to its modelling of small and medium scale behaviour of leachate within the waste mass, and continue to align groundwater flow and contaminant transport models with the engineering design.
SUE13	We will expect future updates of the ESC to improve presentation of models used for site understanding, to improve the clarity of documentation.
SUE14	To better inform the conceptualisation of the overtopping sequence we recommend that the hydrogeological characteristics of the area of land between the vault and cut-off wall are considered for further investigation.
SUE 15	For future updates of the ESC we recommend that a longer period of monitoring data is used to calibrate and build confidence in numerical models developed to support safety assessments.
SUE16	We recommend that future model calibration recognises and uses quantitative tests as part of the calibration process and summarises them appropriately.
SUE17	LLW Repository Ltd should consider use of quantitative analysis to support the qualitative interpretation of groundwater models and build further confidence.
SUE18	LLW Repository Ltd should clearly substantiate its choice of parameters and data ranges used in the calibration of future hydrogeological models.
SUE19	LLW Repository Ltd should make sure that an objective of the routine site environmental monitoring programme is the systematic collection of hydrological and hydrogeological data to support future refinements of the ESC hydrogeological models.
SUE20	LLW Repository Ltd should provide a way of building confidence that there are no other equally valid model parameterisations that would significantly impact the ESC.
SUE21	In future updates of the ESC, we expect this representation in the hydrogeological flow model to be better underpinned, taking into account the variability of the geological media in

Recommendation number	Summary of recommendation
	the unsaturated zone and changes brought about by the trench and vault development and restoration sequence.
SUE22	Future ESC updates should seek to provide a clear linkage between the variant scenario models undertaken and the assessment scenarios utilised in the main ESC assessment. Where appropriate full descriptions of the nature and implication of the variant scenario models should be presented.
SUE23	We expect future updates of the ESC to further explore conceptual model uncertainty as well as realistic alternative conceptualisations.
SUE24	LLW Repository Ltd should seek to better understand the nature and significance of geomorphology and the resulting depositional environment on spatial variability of hydraulic conductivity. Where appropriate the output of these investigations should inform the nature and number of groundwater flow model realisations.
SUE25	We recommend that in future updates of the hydrogeological modelling used to inform the ESC, LLW Repository Ltd should provide a more transparent and structured approach to the treatment of uncertainty in hydrogeological understanding.
SUE26	Before the construction of future vaults we recommend that LLW Repository Ltd aims to better understand uncertainties associated with the variability in the height of groundwater, connectivity and hydraulic head, As future vaults are developed, we expect site-derived information to be used to inform hydrogeological modelling and the engineering design.
SUE27	As the repository is developed, future updates of the ESC should seek to incorporate, where appropriate, further site-derived information together with further improvements in the functionality of the groundwater models. This might include, for example, changes in groundwater height associated with increased sea levels or changes in hydraulically effective rainfall
SUE28	We would like to see the continued collection of hydrogeological information and material properties of the geologies adjacent to and below the future vaults. In particular, we would like to see ongoing characterisation and monitoring of the area covered by the final cap.
SUE29	We recommend that LLW Repository Ltd further reviews its water budget and calculations of HER to assess uncertainties and changes over time and further substantiate the chosen parameter values.
SUE30	LLW Repository Ltd's forward programme should include updates to the site geochemical understanding.
SUE31	LLW Repository Ltd should substantiate that the selected Kd data are consistent with site conditions and review any future developments in the modelling of retardation.

Recommendation number	Summary of recommendation
SUE32	The need to develop and maintain an understanding of the tritium source term should be included in any consideration of future trench monitoring infrastructure requirements.
SUE33	To further reduce uncertainty associated with the extent of the unsaturated zone under the EDA and to support the hydrogeological assessment of the EDA, we recommend that LLW Repository Ltd consider an increased level of site characterisation in this area.
SUE34	For completeness, we recommend that in future, LLW Repository Ltd improves the ESC further by consideration of more extreme, but physically plausible sea level rise scenarios out to 2100, such as the H++ scenario.
SUE35	In between major ESC updates, we recommend that LLW Repository Ltd maintains a good understanding of the latest developments in climate change science, for example the results of the fifth assessment of the IPCC (IPCC 2013), and its potential impact on the ESC projections.
SUE36	As part of the forward programme, we recommend that LLW Repository Ltd keeps up to date with research on short-term and long-term climate change projections.
SUE37	We recommend that LLW Repository Ltd should re-visit technologies and benefits of onsite measurement of isostatic uplift as part of future ESC reviews.
SUE38	The company should maintain a watching brief on the development of understanding long-term changes in storminess associated with climate change, as well as the frequency and magnitude of storm surge events.
SUE39	Due to their importance in determining the rate of erosion and the potential benefits from the use of more site-specific coastal recession models, we recommend that local shallow geological information continues to be collected from ongoing site development activities, cliff exposures and, if required, dedicated investigation programmes.
SUE40	We recommend that future updates of the ESC consider the potential for increased use of information on local shallow geological sequences in the development of site-specific coastal recession models.
SUE41	We recommend that LLW Repository Ltd considers how differences in localised erosion rates resulting from geological heterogeneity and complex coastal geomorphological processes could be better communicated and presented within future updates to the ESC.
SUE42	Although we accept that over the long term storm events will not have a significant impact on the overall predicted coastal erosion rate, such events could become more important as the coast approaches and encounters the LLWR in the future. We recommend that LLW Repository Ltd considers investigating these phenomena further or identifying any national or international studies that support further

Recommendation number	Summary of recommendation
	understanding.
SUE43	We recommend that future updates to the cliff recession models consider the outputs of the geophysical surveys of the site frontage and Drigg barrier carried out in autumn 2009 and the derived clast size distribution sections.
SUE44	We recommend that LLW Repository Ltd maintains ongoing links with wider investigations into the characterisation, assessment and remediation of eroding historical landfills, and incorporates relevant learning into the ESC.
SUE45	We recommend that LLW Repository Ltd considers investigation of the significance of interactions between different erosion processes, including significant thresholds, during coastal erosion processes.
SUE46	LLW Repository Ltd should identify any significant changes to sea defences on the coastline to the north and south of Drigg and assess the implications in future updates of the ESC. This should include changes to the current SMP that could impact on the LLWR.
SUE47	Because of the differences in waste age between the RDA and EDA, we recommend that LLW Repository Ltd should consider the implications of differences in degradation state on erosion between the newer EDA vault waste and the older RDA vault waste.
SUE48	We consider that the monitoring capability adjacent to and within the trench disposals would benefit from increased functionality both before and after the placement of the final capping system.
SUE49	We recommend that the company takes background groundwater concentrations of contaminants into account within the LLWR non-radiological groundwater monitoring programme.
SUE50	Because the elevated background groundwater concentrations of some non-radiological contaminants could be the result of activities external to the LLWR, such as agriculture, we recommend that LLW Repository Ltd considers whether further sampling of up gradient groundwater is necessary to ensure the timely and effective identification and quantification of offsite sources.
SUE51	We recommend that LLW Repository Ltd makes further efforts to improve understanding of background levels of radioactivity in and around the site in the future ESC.
SUE52	We recommend that the company reviews its tritium monitoring capability before the placement of surcharge material onto the trench disposals.
SUE53	We expect the company to take into account the extended operational period of the site in the design of monitoring infrastructure and strategies.

Recommendation number	Summary of recommendation
SUE54	In future updates of the ESC, we would like to see use of site-derived monitoring information wherever practicable and beneficial in the development and calibration of conceptual and assessment models and to inform site understanding.
SUE55	We recommend that LLW Repository Ltd considers how monitoring requirements and priorities will change during the period of authorisation, ensuring that no actions are taken (for example, relating to site engineering) that would unnecessarily jeopardise future monitoring opportunities.
SUE56	We recommend that LLW Repository Ltd reviews the strategy presented in Hayes et al. (2011) to make sure that its recommendations have been appropriately considered.

8. Appendix 3 - Forward Issues

8.1. Introduction

Forward Issues (FIs) raised as a result of our review of the 2011 ESC represent areas that we believe require, or could benefit from, further work or clarification in the future.

FIs are categorised in terms of the importance of the issue (for example the scope for improvement of the ESC against the GRA) and likely effort required to address the issue (Table 4).

Table 4: FI categories

Category	Priority	Explanation
A1	More important, shorter term	An issue that is expected to be important in supporting the delivery of an acceptable update of the ESC in the future and where we believe there is a need to address the issue well in advance of the next major ESC update. LLW Repository Ltd is likely to need to provide substantial additional information, or to significantly change approach. We expect plans to be put in place to address these issues and ongoing reports on progress. Such reporting might, for example, include detailed plans of action, descriptions of proposed approaches, models or data, or results from interim or provisional analyses.
A2	More important, long-term	An issue that is expected to be important in supporting the provision of an acceptable update of the ESC in the future, but where this improvement can be provided over relatively long timescales. LLW Repository Ltd is likely to need to provide substantial further information, or to significantly change approach. We expect ongoing but infrequent reports on progress with these issues. This reporting might, for example, include detailed plans of action, descriptions of proposed approaches, models or data, or results from interim or provisional analyses.
B1	Important, shorter term	Issues of less importance than category 'A'. LLW Repository Ltd will need to provide some additional information, evidence or analysis well in advance of the next major ESC update. Plans should be put in place to deliver this information. Generally we estimate the level of effort needed to address this category of issue will be substantially less than for category A. We expect reports on progress with these issues, but with less emphasis than for Category A.
B2	Important, long-term	Issues of less importance than category 'A'. LLW Repository Ltd will need to provide some additional information, evidence or analysis, but over relatively long timescales or as part of the next ESC update. Generally we estimate the level of effort needed to address this category of issue will be substantially less than for category A. We expect only infrequent reports on progress with these issues and with less emphasis than for

Category	Priority	Explanation
		Category A.
C	Additional evidence / improvements in approach	Of lesser importance but of value in improving the ESC. Issues where we require limited reporting or information in advance of any updated ESC.

We will agree with LLW Repository Ltd when and how it intends to address these issues and will track progress made to resolve them.

8.2. Forward Issues

A summary of FIs raised during our review of the 2011 ESC site understanding and evolution work is provided in Table 5. FIs are reproduced in full in Environment Agency (2015g).

Table 5: Site understanding Forward Issues

Forward Issue number	Title	Categorisation	Summary of issue
ESC-FI-002	Tritium monitoring and establishment of trigger and action levels	B2	LLW Repository Ltd should continue to monitor tritium throughout the period of authorisation in line with our requirements outlined in this FI.
ESC-FI-004	Forward programme	A1	LLW Repository Ltd should further develop and update its forward programme of work to make sure there is continued improvement of the ESC.
ESC-FI-005	Use of monitoring to reduce uncertainties in the ESC	B1	LLW Repository Ltd to collate and integrate monitoring objectives, strategies and procedures in a single document so as to provide evidence of how the forward monitoring programme will be implemented and developed throughout the period of authorisation and linked to the ESC to reduce uncertainties.
ESC-FI-006	Non-radioactive groundwater assessment reporting	A1	LLW Repository Ltd should update the hydrogeological risk assessment for the LLWR for issue by December 2017.
ESC-FI-008	Management of uncertainty	A2	LLW Repository Ltd should further develop the FEPs and uncertainty tracking system (or alternate tools) as a tool to manage uncertainty in the ESC and feed into the forward programme.
ESC-FI-015	Monitoring of colloids	B2	LLW Repository Ltd should implement a proportionate colloidal material monitoring programme to ensure that the conclusions reached in the 2011 ESC will remain valid.

Forward Issue number	Title	Categorisation	Summary of issue
ESC-FI-018	Near field vault and trench experimental programme	B1	LLW Repository Ltd should propose and implement a near field experimental and monitoring programme. This should be capable of providing sufficient understanding of the vault and trench near field environments to support the ESC throughout the period of authorisation.
ESC-FI-019	Monitoring of coastal erosion	B2	LLWR Repository Ltd should develop and implement a coastal evolution monitoring programme. The company should use the output to check assumptions made within the 2011 ESC and to inform continued development of the ESC.
ESC-FI-023	Leachate management strategy	A1	LLW Repository Ltd should produce a leachate management strategy that demonstrates the application of BAT to the management of leachate during the period of authorisation. The company should also investigate long-term leachate drainage performance, degradation and failure mechanisms.
ESC-FI-024	Gas management strategy	A2	LLW Repository Ltd should establish and implement a programme of work to develop a gas management strategy and infrastructure, including collection of necessary monitoring data, for the period of authorisation.
ESC-FI-026	Engineering delivery	A1	LLW Repository Ltd should develop and implement the engineering forward programme to finalise the as-built design so as to allow further construction to begin. This programme should include: • an engineering R&D programme • an engineering performance monitoring programme • the scoping of a proportional Engineering Performance Assessment framework for use in future updates to the ESC.
ESC-FI-028	Improved understanding of the repository erosion process	A2	LLW Repository Ltd should seek to improve its conceptualisation and understanding of the repository erosion sequence.

List of abbreviations

AD	Anno Domini
ALARA	As low as reasonably achievable
AP	After present
BAT	Best available techniques
BIOCLIM	Modelling Sequential Biosphere Systems under Climate Change for Radioactive Waste Disposal (a project within the European Commission 5th Euratom Framework Programme Contract FIKW-CT-2000-00024s)
BIOPROTA	An international collaboration in biosphere research for radioactive waste disposal
BNFL	British Nuclear Fuels Limited
CEAR	Compilation of Environment Agency requirements
CIRIA	The Construction Industry Research and Information Association
CRM	Coastal recession model
Defra	Department for Environment, Food and Rural Affairs
DWS	Drinking water standard
EC	European Commission
EDA	Extended disposal area
EDTA	Ethylene diamine tetra-acetic acid
EPR10	Environmental Permitting (England and Wales) Regulations 2010, as amended
EQS	Environmental quality standard
ESC	Environmental safety case
FEP	Features, events and processes
FI	Forward issue
GBq	Gigabequerel
GRA	Guidance on requirements for authorisation (of near-surface disposal facilities on land for solid radioactive wastes)
GRM	Generalised Repository Model
HER	Hydrologically effective rainfall
HRA	Hydrogeological risk assessment
IAEA	International Atomic Energy Agency
IAF	Issue assessment form
INF	Inventory and near field
IPCC	Intergovernmental Panel on Climate Change

IRF	Issue resolution form
ISO	International Standards Organization
Kd	Partition coefficient or ratio
LIDAR	Light detection and ranging
LLW	Low level waste
LLWR	Low Level Waste Repository near Drigg, Cumbria
LLWRAS	LLW Repository assessment standards
mAOD	Metres above ordnance datum
MBq	Megabequerel
MODARIA	Modelling and Data for Radiological Impact Assessments (IAEA project)
MRVs	Minimum reporting values
mSv	Millisievert
NDA	Nuclear Decommissioning Authority
NNL	National Nuclear Laboratory
NWAT	Nuclear Waste Assessment Team
O&E	Optimisation and engineering
OHSAS	Occupational Health and Safety Advisory Service (standard)
ONR	Office for Nuclear Regulation
PCSC	Post-closure safety case
PEG	Potentially exposed groups
R&D	Research and development
RDA	Reference disposal area
RI	Regulatory issue
RO	Regulatory observation
RSA 93	Radioactive Substances Act 1993 (as amended)
SAC	Special area of conservation
SCAPE	Royal Haskoning's Soft Cliff And Platform Erosion process-based model
SCM	Safety case management
SDP	Site development plan
SI	International system of units
SLC	Site licence company
SMP	Shoreline management plan
SSSI	Site of special scientific interest
SUE	Site understanding and evolution
Sv	Sievert

TBq	Terabequerel
TQ	Technical query
WAC	Waste acceptance criteria

Glossary

Term	Definition
Activity	In radioactive-decay processes, the number of disintegrations per second, or the number of unstable atomic nuclei that decay per second in a given sample.
Adsorb	To gather (a gas, liquid, or dissolved substance) on a surface in a condensed layer.
Anthropogenic	Caused or produced by humans
Assessment code	A code used to assess the performance of some aspect of a system.
Basal drainage layer	A granular drainage layer located below the base of the vault.
Bath tubbing (over-topping)	The phenomenon whereby leachate collects within a disposal facility (e.g. the vaults or trenches) and builds up to such a level that it overflows.
Becquerel (Bq)	Becquerel is the derived SI unit of radioactivity equal to one disintegration per second. Activities are commonly documented in terms of megabecquerels (MBq or 10^6 Bq), gigabecquerels (GBq or 10^9 Bq) and terabecquerels (TBq or 10^{12} Bq).
Best available techniques (BAT)	The latest stage of development (state of art) of processes, of facilities or of methods of operation which indicate the practical suitability of a particular measure for limiting discharges, emissions and waste.
Beta particle	An electron or positron emitted from an atomic nucleus in a certain type of radioactive decay.
Biosphere	The part of the earth's crust, waters, and atmosphere that supports life.
Cap	Engineered layer covering waste in the trenches and vaults to limit the amount of water entering the disposed waste and minimise the risk of intrusion from human and animal activities.
Chelating agents	A chelating agent is a substance whose molecules can form several bonds to a single metal ion.
Colloid	A small particle or molecule dispersed in a second medium that has at least one dimension between approximately 1 nm and 1 µm.
Compartment flow model	A compartment-based numerical model of the LLWR near field used to calculate groundwater flows through the near field.
Complexant	'Complexing agents' are chemicals that can bind strongly to metal ions and significantly increase their solubility or decrease their ability to sorb onto solids. They may be an individual atom, molecule or functional group that binds to

	metal with one or more bonds. The bonding may be ionic or coordinate bonds.
Complexation	Is the process by which a ligand (complexant) and metal bind together to form a new chemical species.
Computer code (or code)	A software implementation of a numerical model that uses a computer processor to solve equations.
Conceptual model	A set of qualitative assumptions used to describe a system, or part of a system, in the real world.
Conservative (of assumptions and data)	Cautious in the sense that impacts would be overestimated.
Cut-off wall	A generic term for a low hydraulic conductivity wall constructed below ground level that is intended to reduce (cut-off) lateral water seepage into or out of part of a site.
Deterministic	A deterministic analysis is one in which each input parameter is assigned a single numerical value, leading to a single value for the result. Typically, deterministic analysis is used with either 'realistic' or 'cautious' values, based on expert judgement and knowledge of the phenomena being modelled.
Differential settlement	Different settlement between two adjacent stacks in the vaults or between adjacent locations of waste in the trenches.
Diffusion	Transport of chemical species along a concentration gradient, within a solid, liquid or gaseous phase.
Disposal	Disposal is the emplacement of waste in a specialised land disposal facility without intent to retrieve it at a later time; retrieval may be possible but, if intended, the appropriate term is storage.
Dose guidance level (for human intrusion)	In the context of near-surface disposal facilities, the dose standard against which the radiological consequences of human intrusion are assessed. It indicates the standard of environmental safety expected but does not suggest that there is an absolute requirement for this level to be met.
Dose rates	The radiation dose (dosage) absorbed per unit of time.
Elicitation	A structured process in which a group of experts are brought together to derive logical theoretical outcomes or to solve problems.
Engineered barrier	A barrier that is designed to protect from human intrusion into disposed waste and minimise the release of contaminants, both radiological and non-radiological, from the disposal facility, consequently minimising the dose to humans and non-human biota.
Environmental permit	A permit issued under the Environmental Permitting (England and Wales) Regulations 2010.
Environmental safety	The safety of people and the environment both at the time of disposal and in the future.
Environmental safety case (ESC)	The collection of arguments, provided by the developer or operator of a disposal facility, that seeks to demonstrate

	that the required standard of safety for people and the environment, both at the time of disposal and in the future, will be achieved.
Extended disposal area (EDA)	An extended area of the repository, beyond but including the Reference Disposal Area, which is considered in the 2011 ESC to be sufficient to dispose of all waste requiring vault disposal in the United Kingdom Radioactive Waste Inventory.
Features, events and processes (FEPs)	Any factors that may influence the disposal system.
Forward issue (FI)	Areas of work that we believe it is important for LLW Repository Ltd to progress as part of its forward improvement plan. Areas where we see scope for continued improvement in the ESC and its implementation.
Fracture flow	Preferential flow of water through fractures in a rock mass.
Gamma radiation	Electromagnetic radiation of extremely high frequency and therefore high energy per photon. Gamma rays are ionizing radiation, and are thus biologically hazardous. They are classically produced by the decay from high energy states of atomic nuclei.
Geological strata	A geological stratum is a layer of sedimentary rock that has internal characteristics that distinguish it from other layers.
Geosphere	The geological formations and subsurface environment through which radionuclides may migrate.
Glaciotectonics	Faulting of geological (and glacial) material resulting from the actions of glaciers during ice ages.
Hydraulic gradient	A measure of the change in groundwater head over a given distance.
Greenhouse gas	Gases whose absorption of solar radiation is responsible for the greenhouse effect, including carbon dioxide, methane, ozone and fluorocarbons.
Groundwater	All water which is below the surface of the ground in the saturated zone and in direct contact with the ground or subsoil.
Gull wing design	A previous repository restoration design incorporating two discrete landforms for the vaults and trenches respectively.
Hydraulic conductivity	A property of soil or rock, that describes the ease with which a fluid (usually water) can move through pore spaces or fractures. It depends on the intrinsic permeability of the material, the degree of saturation, and on the density and viscosity of the fluid.
Infiltration	The process in which a fluid passes into the pores of a solid.
Inorganic	Not having the structure or characteristics of living organisms; not organic.
Inundation	The ephemeral or permanent covering of all or part of the repository by water. Inundation may occur without large scale disruption of the waste.

ISO freight container	A steel container built to standard dimensions defined by the International Standards Organization (ISO), which can be loaded and unloaded, stacked and transported efficiently over long distances without being opened. Currently, most wastes intended for disposal in the vaults at LLWR are placed in half-height ISO containers licensed for LLW transport. The 2011 ESC assumes that this will continue to be the case.
Isostasy/isostatic uplift	The vertical movement of the upper part of the earth's crust in response to the removal of loading associated with the presence of Quaternary ice sheets.
Issue assessment form (IAF)	Issues raised during our review of the 2002 ESCs, which the operators of the LLWR were required to address as part of the development of the 2011 ESC.
Issue resolution form (IRF)	A template form used to record and track issues raised as part of the 2011 ESC review, along with their resolution. Each form provides a record of concerns or questions along with one or more actions for LLW Repository Ltd. LLW Repository Ltd recorded or summarised its response on the form, which was then reviewed by the Environment Agency and closed when a satisfactory response was received.
Leachate	Any liquid which has been in contact with wastes. Leachate is collected in the base of vaults and trenches and arises as a result of the infiltration of rainwater or groundwater.
Lithofacies unit	A subdivision of rock layers distinguished on the basis of similar physical characteristics and facies associations. Lithofacies units have been defined to create a regional three-dimensional model of the geology underlying the LLWR.
Low level waste (LLW)	In government policy, low level waste is defined as 'radioactive waste having a radioactive content not exceeding four gigabecquerels per tonne (GBq te^{-1}) of alpha or 12 GBq te^{-1} of beta/gamma activity'. It consists largely of paper, plastics and scrap metal items that have been used in the nuclear industry, hospitals and research establishments. In future, there will also be large volumes of LLW in the form of soil, concrete and steel, as existing nuclear facilities are decommissioned.
Matrix flow	Flow of water through the matrix porosity of a soil or rock matrix.
Monitoring	Taking measurements so as to be aware of the state of the disposal system and any changes to that state. This may include measuring levels of radioactivity in samples taken from the environment, and also measuring geological, physical and chemical parameters that are relevant to environmental safety and which might change as a result of construction of the disposal facility, waste emplacement or closure.
Near field	In the context of the assessments in support of the LLWR ESC, the near field consists of the waste and engineered barriers.

Optimisation	Optimisation is the principle of ensuring that radiation exposures are as low as reasonably achievable (ALARA) in the given circumstances. It is a key principle of radiation protection recommended by the International Commission on Radiological Protection (ICRP) and incorporated into UK legislation.
Organic	A class of chemical compounds that include carbon within their structure.
Overtopping (bath-tubbing)	The phenomenon whereby leachate collects within a disposal facility (e.g. the vaults or trenches) and builds up to such a level that it overflows LLW Repository Ltd also uses the term 'bath-tubbing' when referring to this phenomenon.
Packer test	Packer tests consist of isolating specific sections of a borehole with inflatable packers (bladders) so that water-quality samples can be collected and aquifer tests can be conducted.
Pathway	A route or means by which a receptor could be, or is exposed to, or affected by a contaminant. Four pathways are considered in the 2011 LLWR ESC: groundwater, gas, natural disruption (coastal erosion) and human intrusion.
Peer review	A formally documented examination of a technical programme or specific aspect of work by a suitably qualified expert or group of experts who have not been directly involved in the programme or aspect of work.
Period of authorisation	The period of time during which disposals are taking place and any period afterwards while the site is under active institutional control.
Permeability	A measure of the capability of a porous rock or sediment to permit the flow of fluids through its pore spaces.
pH	A figure expressing the acidity or alkalinity of a solution on a logarithmic scale on which 7 is neutral, lower values are more acid and higher values more alkaline.
Post-closure safety case	The safety case presented as part of the ESC that covers the time after the end of the period of authorisation.
Process based models	Any model that incorporates a detailed representation of the underlying physical, chemical or biological processes relevant to a system.
Putrescible	Liable to decay – generally used to describe an organic material that will become rotten.
Quaternary	The latest period of time in the stratigraphic column, 0 to 2 million years before present, typically represented by local accumulation of glacial (Pleistocene) and post-glacial (Holocene) deposits.
Radioactivity	The emission of alpha particles, beta particles, neutrons and gamma or x-radiation from the transformation of an atomic nucleus.
Radionuclide	An unstable form of an element that undergoes radioactive decay.

Receptors	Something that could be adversely affected by a contaminant, such as people, an ecological system, property or water body.
Reference case	The baseline set of assumptions about the disposal facility and its evolution with time that is used in the calculations of dose and risk.
Reference design	The engineering design arrived at through optimisation studies within the 2011 ESC. It is used as the basis for detailed assessments of facility performance and radiological and non-radiological impacts within the 2011 ESC.
Reference disposal area (RDA)	The disposal area including the trenches and Vaults 8 to 14.
Regulatory issue (RI)	An issue raised in an issue resolution form during our review of the 2011 ESC where deficiencies in the case were identified. An RI is a deficiency sufficiently serious that, unless or until it is resolved, we will either: (a) not grant a permit; or (b) grant a permit constrained by major limiting conditions (as distinct from information or improvement conditions) defined by us to mitigate the consequences of the RI.
Regulatory observation (RO)	An issue raised in an issue resolution form during our review of the 2011 ESC where deficiencies in the case were identified. An RO is a deficiency not sufficiently serious to prevent us issuing a permit but sufficiently serious that, unless or until it is resolved, we will include an improvement or information condition in the permit requiring defined actions on defined timescales to resolve it (or to demonstrate suitable and sufficient progress towards resolving it).
Retardation	A measure of the reduction in solute velocity relative to the velocity of the flowing groundwater caused by processes such as adsorption.
Risk guidance level	A level of radiological risk from a disposal facility that provides a numerical standard for assessing the environmental safety of the facility after the period of authorisation.
Scenario	One of several possible descriptions of the evolution of the disposal facility and its surroundings from the time of site closure as a result of natural, human-induced, waste-related and engineering-related events and processes.
Site development plan (SDP)	Sets out proposals and assumptions on operations, remedial activities, vault design, capacity and future waste disposal practice, closure design and management up to the end of the period of authorisation. Forms the basis of assessment of repository performance.
Soakaway test	Soakaway tests are normally carried out in trial pits. The pits are filled with gravel to ensure the sides of the trial pit remain stable during charging and draining. The time for 75% of the volume of water to drain away is used as a means of assessing the permeability of the soil

Source term	Description of the characteristics of the waste inventory (for example radioactivity, chemical hazard and volume) used in assessments of environmental impacts.
Stochastic	Stochastic Radiation Effect: A radiation-induced health effect for which the probability but not the severity of the effect is related to the magnitude of the exposure.
Storm surge	A coastal flood or tsunami-like phenomena of rising water commonly associated with low pressure weather systems.
Surcharge	The material added to the top of the waste prior to the engineered cap being placed over the trenches, to induce settlement in the waste materials and thus limit the extent of settlement that the engineered cap will be initially subjected to.
Technical query (TQ)	An issue raised in an issue resolution form during our review of the 2011 ESC where deficiencies in the case were identified. TQs are the least significant of the issues raised and represent a deficiency not sufficiently serious for us to require defined action by LLW Repository Ltd but sufficiently significant that we would request action.
Trench	A trench is an excavation in the ground into which loose waste is tipped.
Uncertainty	Lack of certainty. A state of limited knowledge that precludes an exact or complete description of past, present or future.
Unsaturated	A volume of material is unsaturated when some or all of the pore space is filled with air.
Variant cases	Alternative calculation cases that are defined to investigate the effect of uncertainty in FEPs on the risk and dose calculations.
Vault	A space constructed of reinforced concrete base slabs and walls where wastes are emplaced.
What-if scenario	A low-likelihood scenario put forward to explore the consequences of a defined set of assumptions.

Would you like to find out more about us or about your environment?

Then call us on

03708 506 506 (Monday to Friday, 8am to 6pm)

email

enquiries@environment-agency.gov.uk

or visit our website

www.gov.uk/environment-agency

incident hotline **0800 807060** (24 hours)

floodline **0345 988 1188** (24 hours)

Find out about call charges (www.gov.uk/call-charges)

Environment first: Are you viewing this on screen? Please consider the environment and only print if absolutely necessary. If you are reading a paper copy, please don't forget to reuse and recycle if possible.