Radioactive Waste Management

NDA Report no. DSSC/454/01

Geological Disposal

Biosphere Status Report

December 2016

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Abstract

The Biosphere Status Report is part of a suite of eight research status reports. The purpose of the research status reports is to describe the science and technology underpinning geological disposal of UK higher activity wastes by providing a structured review and summary of relevant published scientific literature and discussing its relevance in the UK context. The reports have been written for an audience with a scientific or technical background and with some knowledge of the context of geological disposal. The current suite of research status reports (issue 2) updates and replaces the suite produced in 2010 (issue 1).

The objective of the Biosphere Status Report is to summarise Radioactive Waste Management Limited's (RWM's) understanding of the biosphere developed through its research programme and the approach adopted to representing the biosphere in the generic Disposal System Safety Case (DSSC). The key message emerging from the analysis presented in this status report is that the current biosphere methodology and models are fully consistent with international recommendations and the present context, and are underpinned by appropriate research. RWM recognises areas that require further development and issues that can only be resolved as the GDF site selection process progresses towards site-specific assessments.

Executive Summary

The Biosphere Status Report is part of a suite of research status reports describing the science and technology underpinning geological disposal of UK higher activity wastes. It provides a summary of the way in which understanding of the biosphere, developed through research activities undertaken by RWM within the UK and through international collaborations, is represented. Emphasis is placed on long-term post-closure safety, whilst areas that require consistency with other aspects of RWM's programme, including operational and environmental impact assessments, are acknowledged.

The biosphere comprises the atmosphere, surface and near-surface environment, normally inhabited by living organisms, including any near-surface aquifers. The biosphere does not constitute a barrier in itself; it is where key end points relating to the effectiveness of the disposal system are determined, including potential environmental concentrations and potential exposures of humans and other organisms in the long-term. The present-day biosphere is important in defining the context within which construction and operation will take place, as well as providing a baseline against which associated impacts can be assessed. The biosphere, including its long-term evolution, is also important in defining the boundary conditions for the geosphere and identifying potential sources of disturbance to the multiple barriers within the disposal system.

The way in which we represent the biosphere in long-term assessments draws on approaches established though collaborative IAEA and EC projects to address requirements described in UK regulatory guidance. That guidance acknowledges the uncertainties associated with assessing safety on timescales extending to hundreds of thousands of years. Quantitative studies conducted within this framework should not be treated as predictions, but should be regarded as broad indicators of environmental safety.

Projections of global climate that incorporate elevated greenhouse gas concentrations indicate that the Earth is very likely to be within an extended interglacial period. Warm climate conditions are anticipated to arise within central England. Boreal and subsequent periglacial landscapes will then develop as the Earth's climate cools towards the next glaciation. The next glaciation is not expected to occur before 170,000 years after-present or longer. We are funding on-going research that seeks to review these long-term climate projections in light of the developing climate science.

In response to climate change, the sea-level around the British Isles is projected to increase by approximately 10 to 20 m within the next few thousands of years. In the far future, sea levels can be expected to fall again as ice sheets increase in size towards future glaciations, falling to tens of metres below the present-day level.

For post-closure assessments, principal focus remains on assessing potential releases to terrestrial/freshwater systems based on the additional dilution that typically occurs with contaminant releases to estuarine, coastal and marine systems. For terrestrial/freshwater systems, assessments have also focused on inland-lowland contexts during the site-generic phase, maximising potential exposure pathways to humans. Extensive agricultural usage remains viable within a UK context throughout the projected warm and temperate periods. Potential doses to human groups remain a primary focus of radiological assessments, though consideration is also given to potential impacts on wildlife and on assessing potential impacts from non-radiological species; we are funding research on wildlife dose assessment.

For post-closure contaminant releases in groundwater, near-surface hydrogeology and catchment-scale hydrology are important factors in determining the degree of dilution of deeper groundwaters as they reach the biosphere, as well as defining potential discharge locations and characteristics. Our research has refined understanding of the potential for impacts of potential contaminant releases in gases from the GDF, with a focus on ^{14}C.

Biosphere models for potential post-closure groundwater releases to terrestrial, freshwater, estuarine, coastal and marine systems are presented. The models are used to convert calculated release rates in groundwater from the geosphere into potential doses. Studies have been undertaken with the model for terrestrial and freshwater releases to explore uncertainties. They demonstrate, for example, that dose factors for infants and children, expressed on a basis of annual committed effective dose, are typically within a factor of two to four greater than those for adults when similar exposure pathways are considered. We will continue to keep our understanding of the biosphere behaviour and potential radiological impacts of key radionuclides under review.

For the operational period of the GDF, potential impacts on the general public are assessed, including those arising from accident scenarios, drawing on Environment Agency guidance. The approach for operational assessments has been updated for ^{14}C to reflect both the gaseous nature of the potential source from the GDF and the improved understanding that has been gained through our research into the behaviour of ^{14}C-bearing gases in the biosphere.

RWM's approach to the biosphere continues to build on work that has been at the forefront of biosphere research over the last 30 years and more, through the instigation of innovative work and through active participation in a variety of international collaborative programmes. The current approach to the biosphere represents the result of a process of continuous enhancement over that period.

The way in which the biosphere is represented in assessments is both adaptable and flexible enough to incorporate future developments, as the programme progresses towards site selection. Continued enhancement of the methodology and tools used will ensure that our biosphere approach remains consistent with the latest scientific understanding, suitable for the current context and prepared for the next stages of the GDF site selection process.

We will continue to update this report, in line with updates to the generic DSSC, as part of each major stage of the GDF development programme. Over time, the design options under consideration and the choices that need to be made will change from an emphasis on strategy to one on implementation. This approach is consistent with a staged development and approval process.

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List of Acronyms

Acronym	Definition
ALLIANCE	The European Radioecology Alliance that maintains and enhances competence in assessing the impact of radioactive substances on humans and the environment
AOGCM	Atmosphere-Ocean General Circulation Models
BIOCLIM	Modelling Sequential Biosphere Systems under Climate Change for Radioactive Waste Disposal, a project funded under the EURATOM fifth framework programme
BIOPROTA	Key Issues in Biosphere Aspects of Assessments of the Long-term Impact of Contaminant Releases Associated with Radioactive Waste Management, a collaborative forum
COMET	Coordination and implementation of a pan-Europe instrument for radioecology, a project funded under the EURATOM seventh framework programme
CORDEX	Co-ordinated Regional Downscaling Experiment
DSSC	Disposal System Safety Case
DSTS	Disposal System Technical Specification
EIA	Environmental Impact Assessment
EMIC	Earth Model of Intermediate Complexity
EPIC	Environmental Protection from Ionising Contaminants
EPR10	Environmental Permitting Regulations 2010
ERICA	Environmental Risks from Ionising Radiation in the Environment: Assessment and Management
FARMLAND	Terrestrial food chain component of PC-CREAM
FASSET	Framework for Assessment of Environmental Impact
FEPs	Features, Events and Processes
GENIE	Grid Enabled Integrated Earth System Modelling Framework
HadCM3	Meteorological Office Hadley Centre AOGCM
HHGW	High Heat Generating Waste
IPT	Integrated Project Team
LLWR	Low Level Waste Repository
LO-RISE	Long-lived Radionuclides in the Surface Environment, one of three consortia funded under the RATE UK research programme
MODARIA	Modelling and Data for Radiological Impact Assessments, an IAEA co-ordinated programme of work
NDAWG	National Dose Assessment Working Group

Acronym	Definition
NERC	Natural Environment Research Council
OESA	Operational Environmental Safety Assessment
PC-CREAM	Software application for performing radiological impact assessments of routine, continuous discharges of radionuclides to the environment
PEG	Potentially Exposed Group
PLUME	Atmospheric dispersion component of PC-CREAM
PROTECT	Protection of the environment from ionising radiation in a regulatory context, a project funded under the EURATOM sixth framework programme
RATE	Radioactivity and the Environment, a UK research programme
SEA	Strategic Environmental Assessment
STAR	Strategy for Allied Radioecology, a project funded under the EURATOM seventh framework programme
TREE	Transfer - Exposure – Effects, one of three consortia funded under the RATE UK research programme
UKCIP	UK Climate Impacts Programme

1 Introduction

1.1 Background

In order to build confidence in the safety of a future geological disposal facility (GDF) for the UK[1], in the absence of potential disposal sites, RWM is developing a generic Disposal System Safety Case (DSSC), which shows how the waste inventory destined for geological disposal could be safely disposed of in a range of geological environments. Background information on geological disposal in the UK can be found in the Technical Background Document [1].

The documents comprising the generic DSSC are shown in Figure 1 and include a number of research status reports ('knowledge base'). The purpose of the research status reports is to describe the science and technology underpinning geological disposal of UK higher activity wastes by providing a structured review and summary of relevant published scientific literature and discussing its relevance in the UK context. The current suite of research status reports (issue 2) updates and replaces the suite produced in 2010 (issue 1).

Figure 2 shows how research status reports underpin different safety cases. They include:

- reports on waste package evolution, engineered barrier system (EBS) evolution [2], and geosphere [3], describing the understanding of the evolution of the specific barriers of the multi-barrier system
- reports on behaviour of radionuclides and non-radiological species in groundwater [4] and gas generation and migration [5], describing the release and movement of materials through the multi-barrier system, including the groundwater and any gas phase formed
- reports on criticality safety [6] and on waste package accident performance [7], describing the behaviour of waste packages and the GDF during low probability events
- a report on the biosphere (this report) [8], describing how we think the biosphere may evolve in the future and how radionuclide uptake might be expected to take place.

Research status reports need to be read in conjunction with other documentation, including:

- the Data Report [9], which describes the values of specific parameters used in the safety assessments based on scientific information presented in the status reports
- the Science and Technology Plan [10], which describes planned future research and development activities.

1.2 Objectives and scope

The objective of the Biosphere Status Report is to summarise RWM's understanding of the biosphere developed through its research programme and the approach adopted to representing the biosphere in the generic Disposal System Safety Case (DSSC). Available

[1] Disposal of higher activity wastes in a GDF is current policy in England, Wales and Northern Ireland. Scottish Government policy is that the long-term management of higher activity waste should be in near-surface facilities. Facilities should be located as near to the sites where the waste is produced as possible.

information is discussed with the aim of providing a sufficiently-detailed evaluation of the implications of key processes to allow its direct use in the development of safety cases. Safety-related considerations are excluded from the scope of this document and are provided solely in the safety cases.

The scope covers all materials currently considered in the inventory for disposal, including Intermediate and Low Level Waste (ILW/LLW), High Level Waste (HLW), spent fuels, uranium (particularly depleted, natural and low-enriched uranium, DNLEU) and plutonium.

Figure 1: Structure of the generic Disposal System Safety Case (DSSC). The suite of research status reports represents the knowledge base.

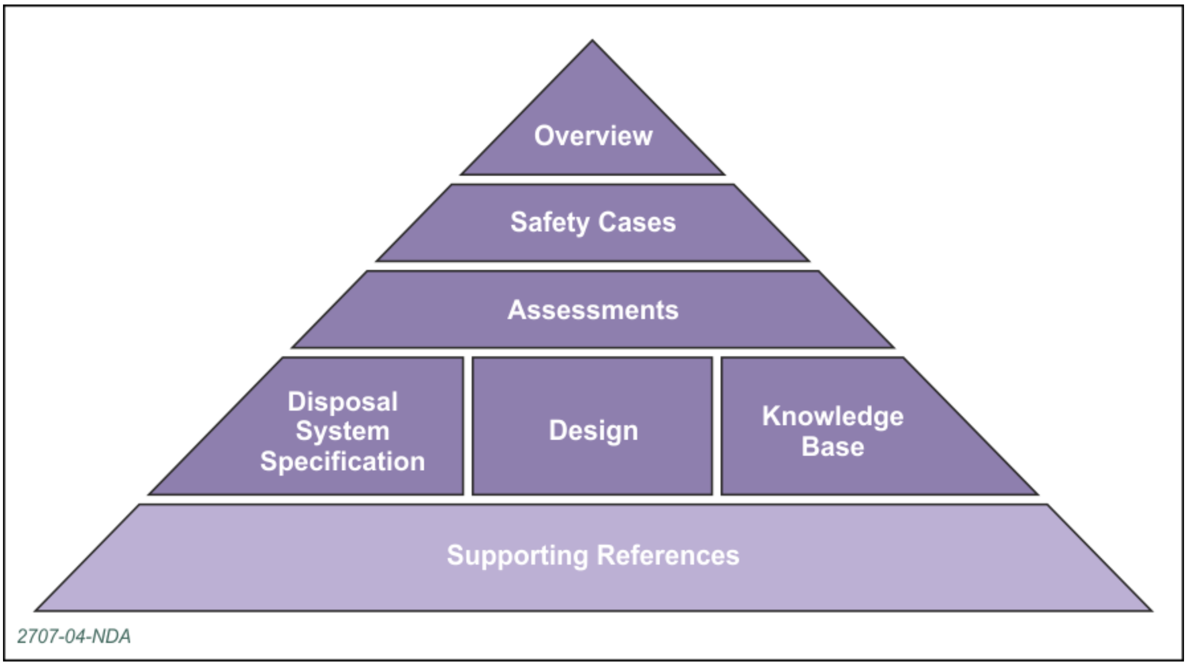
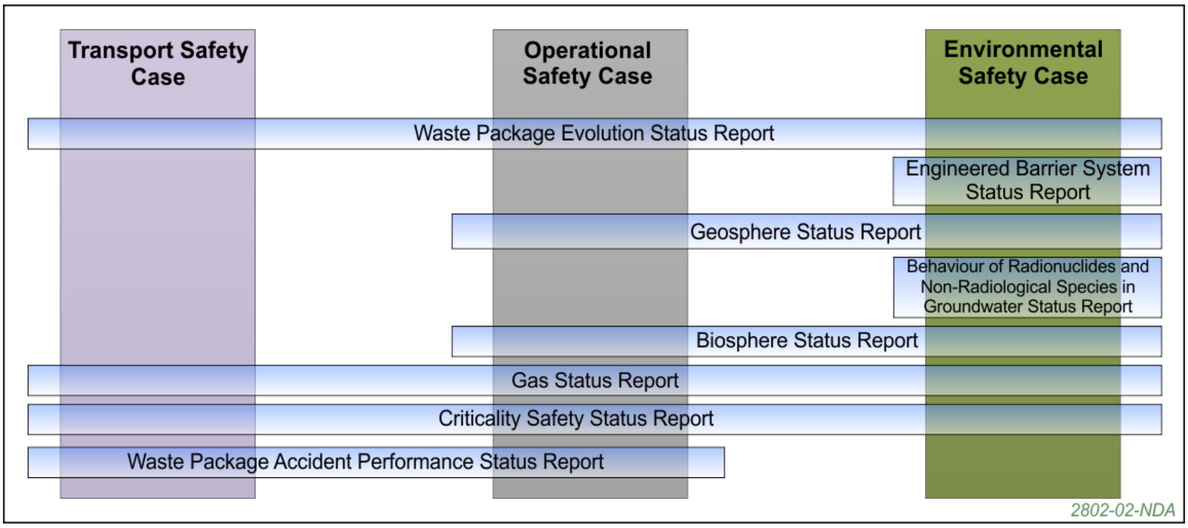


Figure 2: Safety cases and status reports in which underpinning information can be found



1.3 Audience and users

The primary external audience of the status reports is our regulators. The audience is also expected to include academics, learned societies and stakeholders such as the Committee on Radioactive Waste Management (CoRWM) and Non-Governmental Organisations (NGOs). The reports have been written for an audience with a scientific or technical background and with some knowledge of the context of geological disposal. The primary internal user of the information presented in the status reports is RWM's safety case team.

1.4 The relationship with other status reports

Assessments made on the basis of the representation of the biosphere in the long-term explicitly support post-closure safety assessments for geological disposal [11]. Understanding of the biosphere is also used in assessing safety over operational time scales [12]. The treatment and understanding of the biosphere described in this report is used to support the selection of values of specific parameters used in safety assessments and described in [9].

Consideration of processes associated with the long-term development of the biosphere is also important in:

- defining the boundary conditions for the geosphere (for example changes in climate, topography and/or land-use determine groundwater recharge rates and the associated chemistry of the deeper groundwater system)
- identifying potential sources of disturbance (for example the effects of permafrost and glacial scouring) to the different barriers within the disposal system.

In addition, the zone of interaction between the geosphere and the biosphere (termed the 'geosphere-biosphere interface', GBI) influences the extent of any release of potentially contaminated gas and/or groundwater to the biosphere. For contaminated groundwater discharges, the nature of this interface can significantly affect the degree of dilution. Representation of the GBI requires integration of understanding regarding the geosphere and biosphere; the properties of the geosphere are described in the geosphere status report [3].

Gases formed in the GDF may migrate through the engineered barrier system and the geosphere and may eventually emerge in the biosphere. In the case of releases of radioactive gases to the biosphere, the main radionuclides of potential interest are tritium (^{3}H) and ^{14}C, with ^{14}C the only radionuclide relevant to the gas pathway with a sufficient half-life to be of interest on post-closure timescales. The gas status Report [5] documents our understanding of the generation and migration of radioactive trace gases and bulk gases from the GDF.

1.5 Changes from the previous issue

This document updates and replaces the 2010 Biosphere Status Report [13], first published as part of the 2010 generic DSSC suite. Our approach to the biosphere has been established over more than 30 years. The approach is continually kept under review and this issue of the Biosphere Status Report includes the following refinements:

- field, laboratory and modelling studies aimed at improving understanding of the behaviour and fate of ^{14}C released to the soil as gas

- long-term global climate modelling and research into the latest techniques available for downscaling projections to specific locations (MODARIA[2])
- a collaborative UK research programme called TRansfer – Exposure – Effects (TREE)[3], which aims to reduce uncertainty in estimating radiological risks to humans and wildlife
- the UK LO-RISE (LOng-lived Radionuclides In the Surface Environment) project, which is undertaking mechanistic studies of speciation, environmental transport and transfer of radionuclides at four natural analogue locations within the UK
- studies of potential risks from non-radiological species in the GDF to groundwater and the biosphere
- an update to the way in which potential radionuclide releases to terrestrial and freshwater systems are calculated
- an extension to our biosphere modelling capability to include potential releases to estuarine, coastal and marine systems around the UK.

A further change in comparison to the 2010 DSSC is that while this report describes typical values of parameter ranges to support scientific understanding, and as noted above, the generic parameter values and ranges used as relevant examples in the safety assessments are presented in [9].

In line with the objectives of the document and in order to respond to previous feedback, contextual and safety-related information have been removed from the text. Contextual information is provided in [1], while safety-related information is described entirely in the safety case documentation.

1.6 Knowledge base reference period

The knowledge base described in this document contains scientific information available to RWM up to March 2016. Where, within RWM's research programme, progress relative to important topics was made after such date, efforts have been made to reflect such progress up to the publication date of this document.

1.7 Terminology

For information about use of language and terminology in this and other RWM documents please refer to our Glossary [1]. When necessary, we have introduced specific terminology used in the document through the use of footnotes.

1.8 Document structure

The remainder of this report is structured according to the following format:

- section 2 discusses RWM's approach to understanding the biosphere on long timescales
- section 3 describes how long-term biosphere change is addressed
- section 4 describes how the resulting biosphere systems are identified and characterised

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[2] Undertaken in support of Working Group 6 of the International Atomic Energy Agency's (IAEA) programme on Modelling and Data for Radiological Impact Assessments (MODARIA).

[3] TREE is one of three research consortia funded jointly with the UK Natural Environment Research Council (NERC) and Environment Agency through the collaborative Radioactivity and the Environment (RATE) programme. LO-RISE is also funded under the RATE programme.

- section 5 then provides a description of the way in which the biosphere is represented
- section 6 provides a technical summary and conclusions based on our current understanding.

We have used coloured boxes at the beginning of each section to provide a short summary of the key messages and help the reader in following the 'golden thread'.

2 Approach to understanding the biosphere on long timescales

This section describes our broad approach to considering the biosphere on long timescales. The biosphere is first defined (Section 2.1) and the regulatory context defined (Section 2.2) before our approach is described (Section 2.3).

2.1 Definition of the biosphere

The biosphere comprises the atmosphere, surface and near-surface environment, normally inhabited by living organisms, and is taken to include any near-surface aquifers. The biosphere acts as the receptor for any contaminants released from the geosphere and does not constitute a barrier within the disposal system.

The biosphere acts as the receptor for any contaminants that may be released from the geosphere, defines their distribution in the environment; and is where key end-points relating to the effectiveness of the disposal system are determined. This includes potential environmental concentrations and potential exposures of humans and wildlife. The biosphere therefore provides a context for determining the consequences of potential releases of radionuclides and other contaminants from the deeper disposal system and does not constitute a barrier in itself.

An illustration of the biosphere is provided in Figure 3, which also illustrates the main groundwater pathways. Definitions of the main components of the biosphere are provided in Table 1.

Figure 3 Components of the biosphere

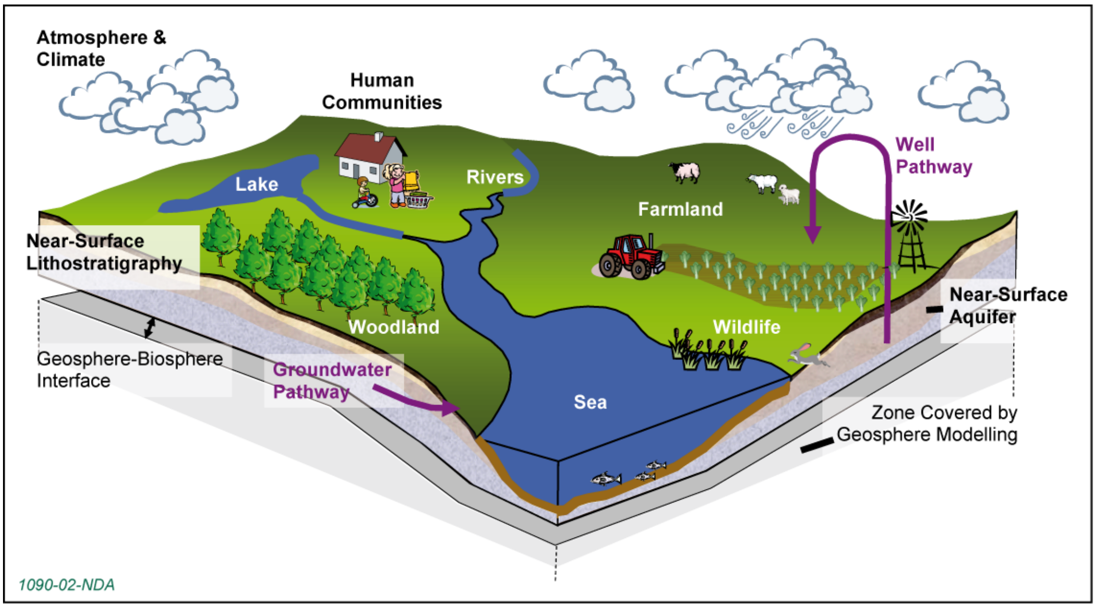


Table 1 Principal components of the biosphere as identified

Principal Component	Definition
Climate and atmosphere	Climate is the expression of meteorological parameters within an area over a minimum of a 30 year period. Here atmosphere refers to the layers of gases surrounding the earth.
Water bodies	Water bodies are the surface and subsurface water masses and may include near-surface aquifers, ice-sheets, estuarine, coastal and marine systems.
Human activity	Human activity describes the nature of the communities, their habits, level of technology and degree of subsistence.
Biota	Biota are the terrestrial and aquatic plant and animal life in the biosphere system. Humans are not included in this component, but rather are included under human activity.
Near-surface lithostratigraphy	Near-surface lithostratigraphy describes the general characteristics of soils and sediments including both their composition and structure.
Topography and bathymetry	Topography and bathymetry are the configuration of the Earth's land surface and depth of lake or sea floors, respectively, including relief and relative positions of natural and man-made features.
Geographical extent	Geographical extent defines the boundaries and/or spatial domain of the biosphere under consideration.
Location	Location is the position of the biosphere system on the Earth's surface.
Catchment	Surface-water catchments into which contaminated groundwater might be released.

2.2 Regulatory context

The regulatory context for geological disposal emphasises that quantitative studies should not be treated as predictions, but should be regarded as broad indicators of environmental safety.

Regulatory guidance on geological disposal for England, Wales and Northern Ireland was updated in 2009 [14] following public consultation. The guidance, summarised in Box 1, emphasises that the results of biosphere assessments in the post-closure phase can only be regarded as broad indicators of environmental safety. The results cannot be taken as predictions of actual impact, rather, they represent a range of plausible indicators of possible impact [15].

Box 1: Key aspects of the regulatory guidance relating to post-closure biosphere studies [14]

- Expectations regarding human health protection are primarily defined in terms of a numerical risk guidance level or target to a person representative of those at greatest risk
- Assessment of the highest annual individual risks to humans is unlikely to be sufficient on its own to establish the environmental safety case due to uncertainties inherent in making long-term projections
- The guidance recognises that some uncertainties cannot be precisely quantified in the long-term and that different potential evolutions of climate or landscape are relevant.
- The guidance also recognises that any calculations will involve assumptions that are somewhat arbitrary and emphasises that they should be plausible, internally consistent and should tend to err on the side of conservatism
- Studies should enable identification of a person representative of those people at greatest risk through definition of potentially exposed groups (PEGs)
- The habits, behaviour and metabolic characteristics of the relevant individuals should be similar to those observed in present-day populations
- Studies should enable conclusions to be drawn that proper protection of the environment will be achieved (encompassing wildlife dose assessment and protection of habitats)
- Collective dose estimates should be calculated up to no more than several hundred years post-closure and are therefore of limited relevance to post-closure assessments for geological disposal [16, 17, 18]
- Standards of protection for non-radiological hazards should be at least consistent with those for authorising disposal of non-radiological hazardous wastes.

2.3 Biosphere approach

The approach to the biosphere has been established over more than 30 years. Stylised assessment-level models of the biosphere are supported by process modelling and research. As the GDF programme advances, biosphere models will become more site-specific.

2.3.1 International Collaboration

RWM's approach to the biosphere draws on international guidance and collaboration, but also recognises that the environmental and regulatory context differs between the UK and other countries.

The way in which the biosphere is represented in post-closure studies for geological disposal of radioactive waste in the UK has been established over more than 30 years and has included working collaboratively with other organisations internationally to share knowledge and establish good practice. This approach has enabled the UK geological disposal programme to provide key inputs to international recommendations relating to biosphere assessment. RWM's approach to the biosphere is intentionally flexible, enabling it to develop in line with the context for geological disposal in the UK as well as developing international recommendations. Consistent with developing recommendations of the International Commission on Radiological Protection (ICRP) [19], in addition to ensuring the protection of humans, the potential impacts on wildlife are taken into account in RWM's consideration of the biosphere. The EU-funded FASSET, EPIC, ERICA and PROTECT projects [20] have been leading towards an agreed approach for assessing potential impacts on wildlife and RWM is supporting on-going developments through the IAEA MODARIA and NERC TREE programmes.

Our approach to the biosphere (described in the following subsection) is therefore based on a long period of continuous development and research. It is fully informed by developments by both international organisations and overseas waste management organisations, but recognises that the environmental and regulatory context differs between the UK and other countries with relatively advanced programmes in this area, such as France, Finland and Sweden. These regulatory approaches have been compared by the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development (NEA/OECD) [21].

2.3.2 RWM approach to biosphere assessment

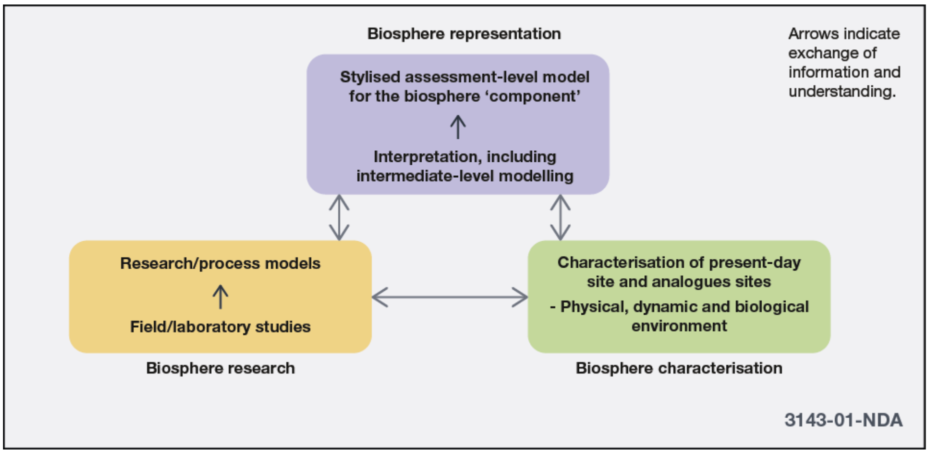
Stylised assessment-level models of the biosphere are supported by more detailed process modelling which, in turn, builds on biosphere research and characterisation. An important consideration is the long timescales, meaning that research has included consideration of long-term climate change and landform evolution.

A primary driver for considering the biosphere on long timescales is the capability to provide quantitative estimates of potential radiological impacts for comparison against regulatory criteria as part of the safety case for geological disposal. Given the uncertainties inherent in projecting long-term changes in characteristics of the biosphere, RWM focuses its research on the main controls on radionuclide transport and distribution within the biosphere rather than on mechanistic details of the processes involved. The aim is to maintain a balance between keeping the approach as simple as can be justified, whilst demonstrating a thorough understanding of the system. This is achieved through a hierarchical approach in which the stylised assessment-level models are supported by more detailed and process-based modelling which, in-turn, builds upon scientific understanding, biosphere research and characterisation, see Figure 4.

In the past, national and international safety cases have concentrated on potential radiological impacts on humans, with particular emphasis on those likely to receive the highest level of exposure, analogous to the critical group in operational safety assessments. However, over recent years increased consideration has been given to the need to explicitly demonstrate that the environment as a whole is also adequately protected against adverse effects [19]. For this reason, potential impacts on wildlife may need to be explicitly considered in future. Note that a preliminary assessment of potential impacts on wildlife from the GDF is given in the Operational Environmental Safety Assessment (OESA) [12].

The main potential impacts on humans and the environment from the GDF are associated with releases of radionuclides. It is however recognised that the GDF will also contain non-radiological species, including heavy metals, organic contaminants and substances that exhibit both radiotoxicity and chemical toxicity (for example uranium). Therefore, assessments are also undertaken to evaluate the impacts of potential releases of such substances.

Figure 4 Relationship between biosphere research, characterisation and modelling



The long timescales relevant to post-closure assessment mean that the surface environment will change from that which is present today. This means that, from the outset, the research and assessment programme has included consideration of issues relating to climate change and landform evolution [22, 23]. Indeed, as discussed in Section 3.2, important developments in long-term climate modelling and quantitative geomorphology have been initiated by organisations concerned with the management of solid radioactive wastes. The long timescales also mean that careful consideration will be given to the use of information from biosphere characterisation of any site, given that the future environment will differ from that at the present-day. Biosphere characterisation will also inform the EIA/Strategic Environmental Assessment (SEA) and Operational Environmental Safety Assessment (OESA).

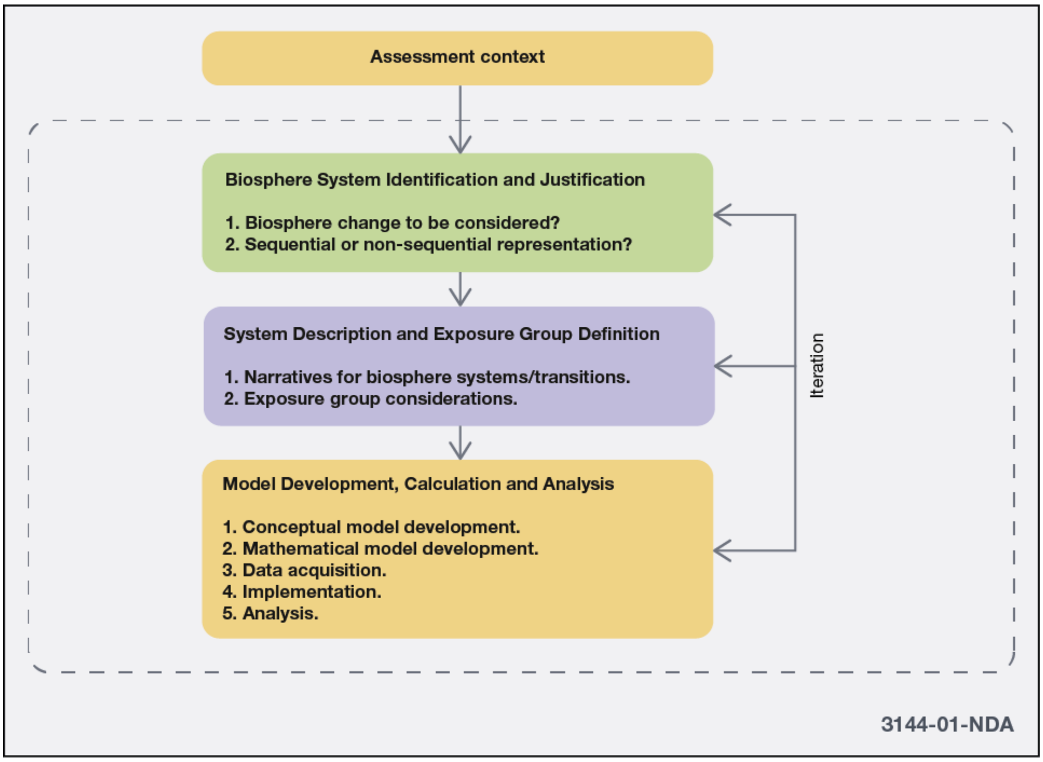
2.3.3 Biosphere methodology

The BIOMASS methodology (developed within the context of an IAEA programme) provides a structured and transparent framework for developing biosphere representations appropriate to the context being addressed.

RWM's approach to representing the biosphere in long-term performance studies aligns with international guidance, notably the BIOMASS[4] methodology developed within the context of an IAEA programme [24]. The approach aims to establish a logical audit trail to justify the scope, constituents and definition of the biosphere. A structured approach is used to define biosphere systems that appropriately reflect the context for each assessment and that can then be used as a basis for quantitative calculations. The approach, which is also reflected in the structure of this report, is illustrated in Figure 5 and is described in more detail below. Although the methodology focuses on biosphere assessment, the importance of scenarios and narratives of biosphere development over time in defining boundary conditions and as inputs to other aspects of the assessment of the safety of the disposal system is acknowledged.

[4] The IAEA is currently considering a new project to review the BIOMASS methodology in light of the developments that have taken place since BIOMASS – see task 003 of our Science and Technology Plan for Geological Disposal [10].

Figure 5 Biosphere methodology



Note: From [25] and based on [24].

A fundamental feature of the methodology is the recognition that assessments are always performed in a particular context. A clear definition of the context provides guidance for the required assumptions, helping to ensure that the assessment is internally consistent and fit-for purpose. The current context is summarised in Table 2, consistent with the structure recommended by BIOMASS [24].

RWM's approach is supported by the identification of Features, Events and Processes (FEPs) of potential importance (see Section 4.3 and [26]). The use of FEP analysis for this purpose has been widely endorsed by international organisations such as the IAEA and the NEA/OECD. FEPs can be distinguished into those that are external or internal to the disposal system and its geographical setting. Internal FEPs characterise the disposal system, whereas external FEPs induce changes in the system. Screening of external FEPs helps to identify scenarios of future evolution that merit consideration (see Section 3.1). Auditing of conceptual and mathematical models against a list of internal FEPs helps to give confidence that nothing of potential importance has been overlooked.

Table 2 Current context for biosphere studies

Category	Description
Purpose:	The primary purpose of biosphere modelling undertaken at the current stage of the site-selection process is to support a broad comparison between alternative environmental settings. Whilst the focus is on qualitative comparisons, some indication of the absolute magnitudes of calculated doses and risks is relevant, because the significance of projected differences in the performance of options will depend on the extent to which there is confidence in their ability to satisfy radiological protection objectives. Biosphere modelling therefore aims to provide site-generic standardised conversion factors between fluxes of radionuclides from the geosphere and effective dose rates to representative persons for various types of environmental setting (biosphere dose conversion factors).
Endpoints:	Although there is a requirement to provide an overall evaluation of potential impacts on the environment, the primary endpoint for the purpose of guiding decision making remains the increment in annual individual radiological risk above the background level associated with naturally occurring radionuclides and other potential sources of contamination, which is to be compared against the risk guidance level given by the environment agencies [14].
Philosophy[5]:	Deterministic calculations and, where necessary, associated sensitivity analyses are preferred for the biosphere assessment over probabilistic analyses. The assumptions required to support the calculations should be plausible, internally consistent and should tend to err on the side of conservatism. There will generally be little need to make use of detailed, process-based models, since no specific sites are considered – however, some reference to such models may be required to avoid making assumptions as to parameter values for assessment models that could not be realised in practice.
Societal Assumptions:	Habits, behaviour and metabolic characteristics are assumed to be similar to those observed in present-day populations, though not necessarily at the site (for example from analogue regions if climatic conditions that differ from those at the present-day are being addressed). There are assumed to be no major advances in technology which, amongst other things, might facilitate radically improved radiation monitoring, or developments in radiation protection science, or in cancer risk management that could mitigate health risks arising from radiation exposure. Neither is a regression in technology assumed.
Biosphere Site Context:	Generalised assumptions are adopted based on typical classes of environment that may need to be considered (see [27]). The site-generic nature of assessments means that the biosphere is defined with a minimum of detail.

5 The 'assessment philosophy' relates to the management of uncertainty, in particular, the approach to parameter uncertainty and the degree to which cautious assumptions are appropriate, see [24].

Category	Description
Source Term and Geosphere-Biosphere Interface:	The nature of the release to the biosphere needs to be consistent with the geological environment. For generic assessments, both contaminated natural groundwater discharge and abstraction of contaminated well water are considered, along with potential gas release. For assessments associated with specific geological environments, there may be a need to compare alternative types of release to the biosphere in order to determine which is most limiting from a radiological protection perspective (for example, [27]).
Timeframes:	It is likely to be convenient to define a number of different timeframes over which results will be presented, and to define appropriate biosphere and geosphere-biosphere interface characteristics for each alternative geological environment and timeframe.

The assessment context does not preclude consideration of biosphere change. That being the case, the mechanisms causing change need to be identified, together with their potential impacts on the biosphere, for example climate change, associated sea-level rise, and their impacts on landscape evolution [23]. This approach leads to the identification of qualitatively different future evolution scenarios that need to be taken forward in the assessments. The scenarios are informed by supporting studies, including downscaling of global climate modelling and consideration of landscape evolution; these are drawn together with an understanding of potential radionuclide releases to form narratives to be represented in assessments.

Descriptions of biosphere systems and transitions can be developed for each future narrative. The descriptions can be developed through consideration of the principal components of the biosphere, together with their interactions. Modelling can be used to provide confidence in the plausibility of assumptions required to support the biosphere descriptions, for example catchment-scale hydrological modelling. Human behaviour, particularly relating to potentially exposed groups, forms a component of the biosphere descriptions.

Conceptual models of contaminant migration and exposure are developed from the biosphere descriptions, which then provide the basis for mathematical models. Parameterisation of the models builds on the biosphere descriptions and guidance provided in the assessment context relating to the treatment of uncertainties. The models can then be implemented in an appropriate calculation tool for analysis, including consideration of the potential effect of conceptual, mathematical and parameter uncertainties.

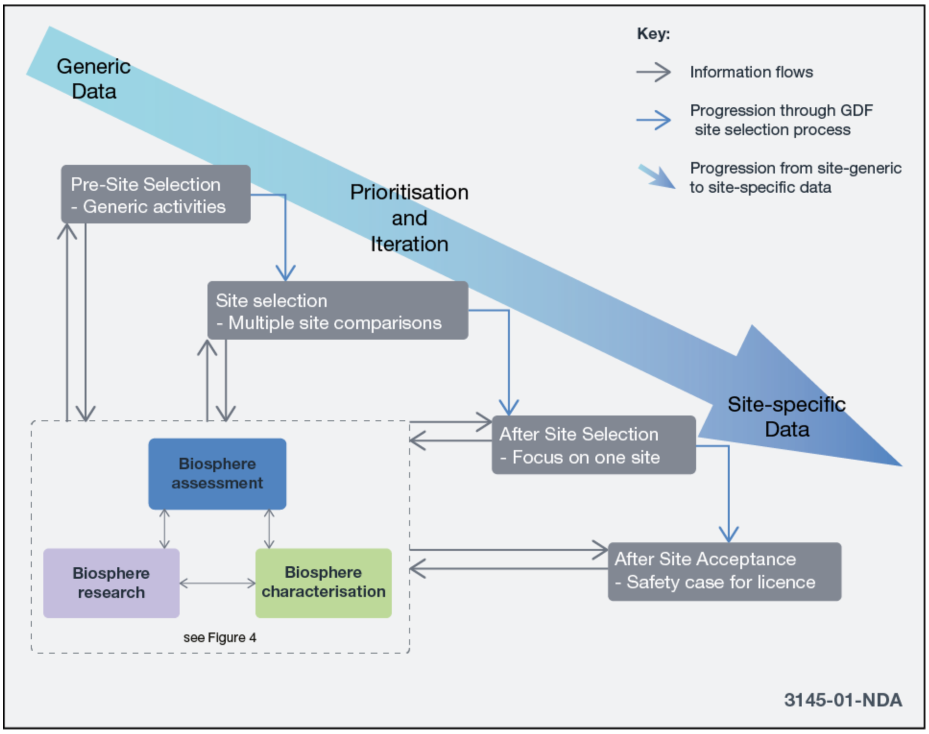
The potential for iteration both within and between the different steps of the biosphere assessment methodology is an important feature of the approach. This recognises the potential for changes and allows for feedback to reflect improvements in understanding and insight relating to biosphere systems and their evolution brought about by the methodology's application [24]. As illustrated in Figure 4, the biosphere assessment is supported by understanding of the key processes developed through research.

2.3.4 Site-specific considerations

The amount of information and understanding about the biosphere will increase as the GDF programme advances towards site selection.

As the GDF site selection process progresses, greater emphasis will be placed on local characteristics observed at the present-day and established through surface investigations at the candidate sites [28, 29] (see Figure 6). Biosphere characterisation studies will be of relevance to the Environmental Safety Case (ESC), the OESA and the Environmental Impact Assessment (EIA), for example in establishing baseline characteristics. There will be a need to co-ordinate addressing the overlapping characterisation needs and to ensure consistent and/or integrated conceptualisation and interpretation across these different aspects of the geological disposal programme.

Figure 6 Prioritisation and iteration as the GDF site selection process moves forwards



Note: Figure adapted from [30].

Process-based modelling will aid in the interpretation of conditions observed at the present-day and will help to demonstrate that an adequate understanding of the site is emerging from the surface-investigation programme to support the safety cases and EIA [31]. Some present-day characteristics, for example, the general topography and local drainage network, are likely to be preserved over thousands to tens of thousands of years, as are the overall structure of the near-surface deposits and the relationship of those deposits to the underlying solid geology [32].

3 Environmental change

The biosphere will change on the long timescales of relevance to geological disposal of radioactive wastes. The processes that result in environmental change have been identified (Section 3.1), leading us to focus on climate change and future human actions. The timeframe of relevance to post-closure safety encompasses projected periods of warmer and colder climate. This section describes how environmental change is treated, with an emphasis on climate (Section 3.2), sea-level (Section 3.3) and landscape evolution (Section 3.4).

3.1 Defining future biosphere systems

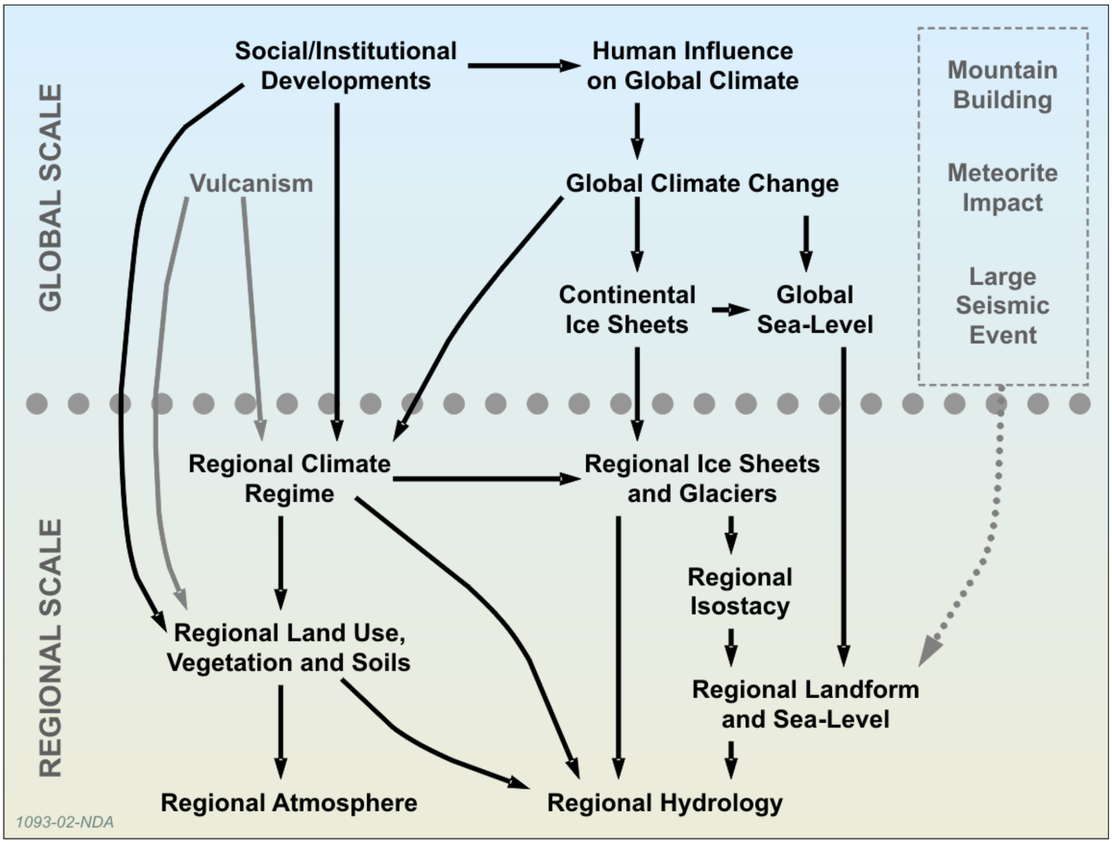
The relatively stable geological context of the UK means that climate change and future human actions are the primary external factors that will determine environmental change.

Given the long timescales involved in performance studies for geological disposal, it is appropriate to take biosphere system change into account. Therefore, it is necessary to identify and justify the selection of environmental change mechanisms and their impacts on the biosphere system. It is also necessary to decide whether these changes can be addressed through calculations for a set of time-independent biosphere states considered in isolation (the non-sequential approach) or whether a sequence of such states and the transitions between them needs to be explicitly represented (the sequential approach).

Our approach to defining future biosphere systems that merit consideration is based on consideration of external FEPs causing environmental change. A schematic illustration of external FEPs and their influence on the biosphere is given in Figure 7. In addition, RWM has given consideration to the long-term effects of external FEPs on the geosphere through a review of natural processes undertaken by the British Geological Survey [33].

The UK is not located close to any major tectonic boundaries and the GDF will be located in a stable geological environment. Therefore, whilst RWM maintains a watching brief on this topic until a site is selected, on a timescale relevant to post-closure safety assessment, vulcanism, large-scale seismicity and mountain building are unlikely to be of any direct significance [33, 34], though their potential influence on global and regional climate change is taken into account. Furthermore, as large meteorite impacts are rare (about every 100 million years) it is highly unlikely that such an event would impact on the local environment of a geological disposal facility over the assessment timescale [34]. Therefore, our focus is on climate change, together with future human actions, as the major factors that determine biosphere change [25, 35].

Figure 7 Illustration of the external features, events and processes model for describing the influence of change on the biosphere system



Note: Figure based on [24]. External features events and processes in grey text are screened out from consideration, as discussed in Section 3.1.

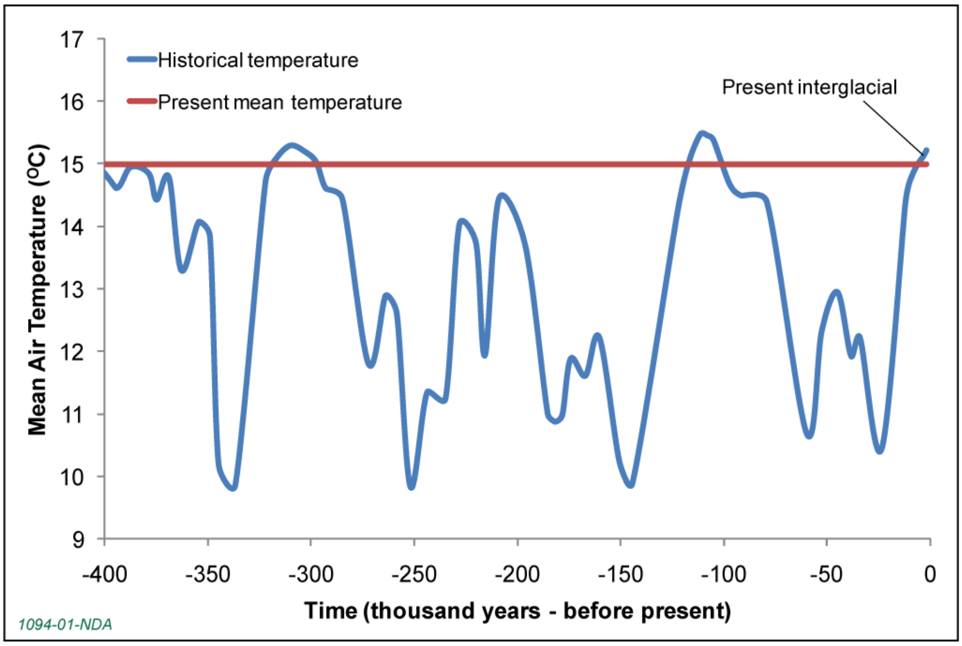
3.2 Future climate

Projections of global climate that incorporate elevated greenhouse gas concentrations indicate that the Earth is within an extended interglacial period. Warm climate conditions are anticipated to arise within central England followed by gradual cooling through boreal and periglacial conditions until a future glacial episode, which is not projected to arise for at least 170,000 years.

On timescales relevant to siting, construction, operation and closure of the GDF, RWM's consideration of climate change draws on guidance established at a national level, notably through the UK Climate Impacts Programme (UKCIP) [36]. Climate change is relevant to all aspects of RWM's programme and not just the biosphere component, since it influences, for example, the overall hydrogeological environment. On timescales of one or two hundred years, anthropogenic emissions of greenhouse gases represent the principal focus. When future climate is assessed on longer timescales, consideration is first given to natural variations before the additional potential impact of emissions caused by man are taken into account [23].

The Earth's climate goes through glacial-interglacial cycles due to: (i) changes in the planet's orbit, which result in natural variations in the input of solar radiation (insolation), and (ii) through natural changes in greenhouse-gas concentrations in the atmosphere (see Figure 8). However, the limited degree of variation of insolation due to changes in the Earth's orbit over the next 50,000 years [37], together with greenhouse gas releases from the combustion of fossil fuels, are projected to lead to the present interglacial period extending for up to 170,000 years from the present-day, or even longer. Future climate change was explored in detail in the BIOCLIM project [38], which drew on the broad international programme of research on climate change, in particular the work of the Intergovernmental Panel on Climate Change (IPCC).

Figure 8 Historical global temperature variations[6] illustrating glacial/ interglacial cycling



Note: Figure based on [39].

RWM continues to keep the science supporting projections of climate change under review. Climate modelling has developed significantly since the BIOCLIM work was originally undertaken, more than ten years ago. RWM is therefore participating in Working Group 6 of the international collaborative MODARIA project[7] [40], which aims to review the representation of environmental change in safety assessments for radioactive waste disposal, with a particular focus on long-term climate change. Through our contribution to Working Group 6, and in support of the programme for geological disposal in the UK, we are supporting work to explore the implications of more recent developments in climate modelling [23], taking into account the latest review and recommendations of the IPCC [41] (see also Box 2).

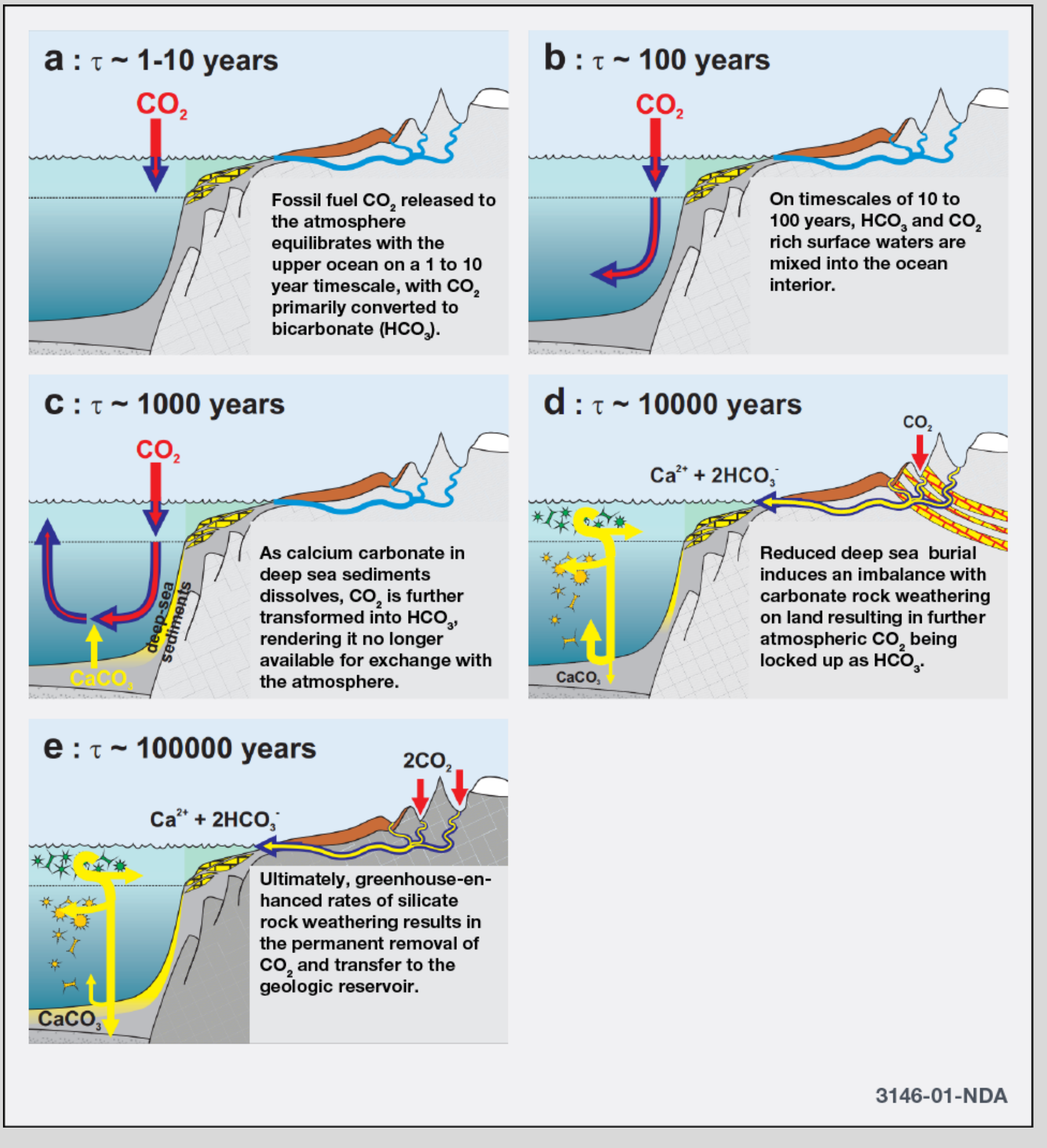
[6] Temperature inferred from ice volume derived using oxygen isotope measurements from ice cores.

[7] Task 032 of the Science and Technology Plan for Geological Disposal [10].

Box 2 RWM research into long-term climate change

In support of MODARIA Working Group 6, RWM is funding work at the University of Bristol to further develop modelling approaches to assessing climate changes at spatial scales ranging from global down to about 10 kilometres. Initially, the Grid Enabled Integrated Earth System Modelling Framework (GENIE) Earth Model of Intermediate Complexity (EMIC) has been used to develop relationships between amounts and patterns of emission of carbon dioxide to the atmosphere from human activities and time-dependent atmospheric concentrations of carbon dioxide over the next few hundred thousand years. In principle, the relationship between emissions and atmospheric concentrations could be complex. However, in practice, it has been found that a rather simple multi-exponential relationship, with the coefficients varying with the total amount of carbon dioxide emitted, is sufficient to simulate future changes in atmospheric concentrations for any time-dependent pattern of emissions and on timescales ranging from about 10 years to about one million years (see Figure 9) [42, 43].

Figure 9 Processes controlling carbon dioxide concentrations in the atmosphere on different timescales (τ) [42]



Box 2 (continued)

Currently, a large number of Atmospheric-Ocean General Circulation Model (AOGCM) simulations are being undertaken using models developed by the UK Meteorological Office. These 'snapshot' simulations are for a wide variety of alternative configurations of the orbit of the Earth, atmospheric carbon dioxide concentrations, and ice sheet distributions. The results from these simulations are being incorporated in a new software tool that will facilitate projections of the climate of the Earth in general, and the British Isles in particular, and at a higher resolution, for any specified emissions scenario and over a timescale extending several hundred thousand years into the future.

In BIOCLIM, overall scenarios for future variations in concentrations of atmospheric carbon dioxide were obtained by combining the contribution from fossil fuel use with projected natural variations. The following three scenarios were considered [44][8]:

- baseline: Natural variations only with no further contribution from fossil fuel combustion beyond historical (late nineteenth century) levels
- low fossil fuel usage: Natural variations plus a contribution from the low future use of fossil fuels (based on 3160 GtC[9] emissions to 2300 years after present)
- high fossil fuel usage: Natural variations plus a contribution from the high future use of fossil fuels (based on 5160 GtC emissions to 2300 years after present).

Many alternative scenarios could be selected; however, these three represented a reasonably comprehensive range based on the information available at the time. They are illustrated in Figure 10.

For application to biosphere studies, projections of future global climate change need to be downscaled to the regional and local areas relevant to the site in question. The BIOCLIM modelling strategy involved defining sequences of climate states in specific regions, such as central England, for each of the climate scenarios studied. Long-term simulations of future climate performed using several types of climate models provided the global and regional climate setting. Semi-qualitative rule-based techniques were then used to downscale these results to the specific regions considered. Subsequent to BIOCLIM, there have been substantial developments in approaches to downscaling and international work on this topic is now co-ordinated through the international Co-ordinated Regional Downscaling Experiment (CORDEX) [45]. The work of CORDEX is being taken into account in MODARIA Working Group 6 and RWM's ongoing work will take account of the recommendations arising from this initiative.

As part of the work contributing to MODARIA Working Group 6 quantitative statistical-physical techniques, which were also explored to some extent in BIOCLIM, have been explored for downscaling the global climate projections to provide results with a spatial resolution of substantially less than the intrinsic AOGCM resolution of one to two degrees [46].

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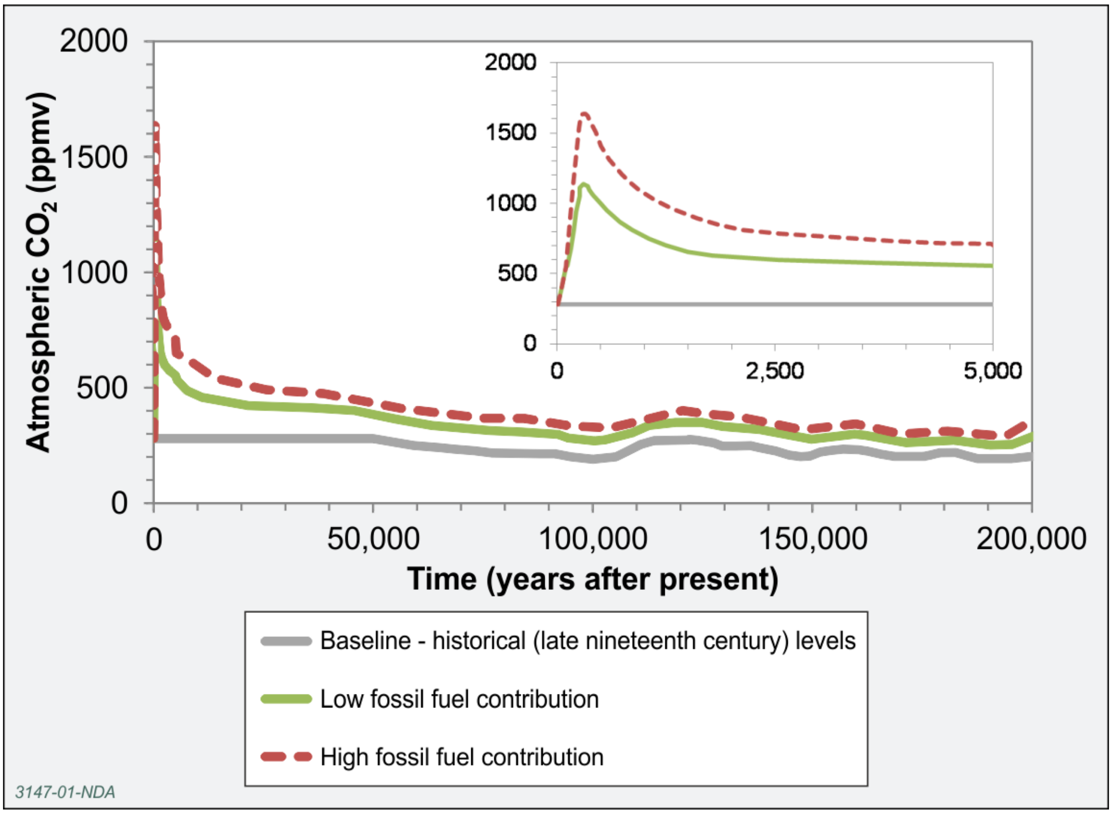
[8] The nomenclature for the climate scenarios has been simplified for this report. The baseline, low and high fossil fuel usage scenarios here refer to BIOCLIM scenarios A4a, B3 and B4, respectively. These scenarios took account of IPCC recommendations over the 21st century and gave consideration to potential uses of known reserves of fossil fuels in the longer term. Low future use implied significant restrictions on the utilisation of currently economic reserves whereas high future use implied little such restriction. Potential future discovery and exploitation of new reserves or the exploitation of currently grossly uneconomic reserves were not included.

[9] 1 GtC = 10^{15} g of carbon.

Figure 10 Projected atmospheric CO_2 concentrations



Notes: Figure abstracted from [47]. The small inserted chart provides increased resolution over the first 5,000 years. The decreases in concentrations observed in the Low and High fossil fuel scenarios after a few hundred years occurs because fossil fuel reserves are largely exhausted or cease to be used. The historical (late nineteenth century) concentration of atmospheric carbon dioxide was about 280 ppmv and the current concentration is about 400 ppmv. Thus, the Baseline case does not include fossil fuel emissions over the period since the late nineteenth century.

Until the MODARIA Working Group 6 work is complete, our biosphere models continue to draw on the climate projections and downscaling undertaken within the BIOCLIM project. Table 3 summarises the classification scheme used in BIOCLIM to characterise the climate states.

Table 3 Classification scheme used to describe climate states

Climate Group	Monthly Temperatures	Climates	Notes
Sub-tropical	Over 9ºC in 8 to 12 months	Subtropical rain Subtropical summer rain Subtropical winter rain	Mediterranean-type climates
Temperate	Over 9ºC in 4 to 7 months	Temperate oceanic Temperate continental	Present-day UK climate
Sub-arctic	Over 9ºC in 1 to 3 months	Subarctic oceanic Subarctic continental	Boreal Periglacial forest tundra
Polar	Not over 9ºC	Tundra Ice	Periglacial (permafrost) Full glacial

Note: Table based on [48].

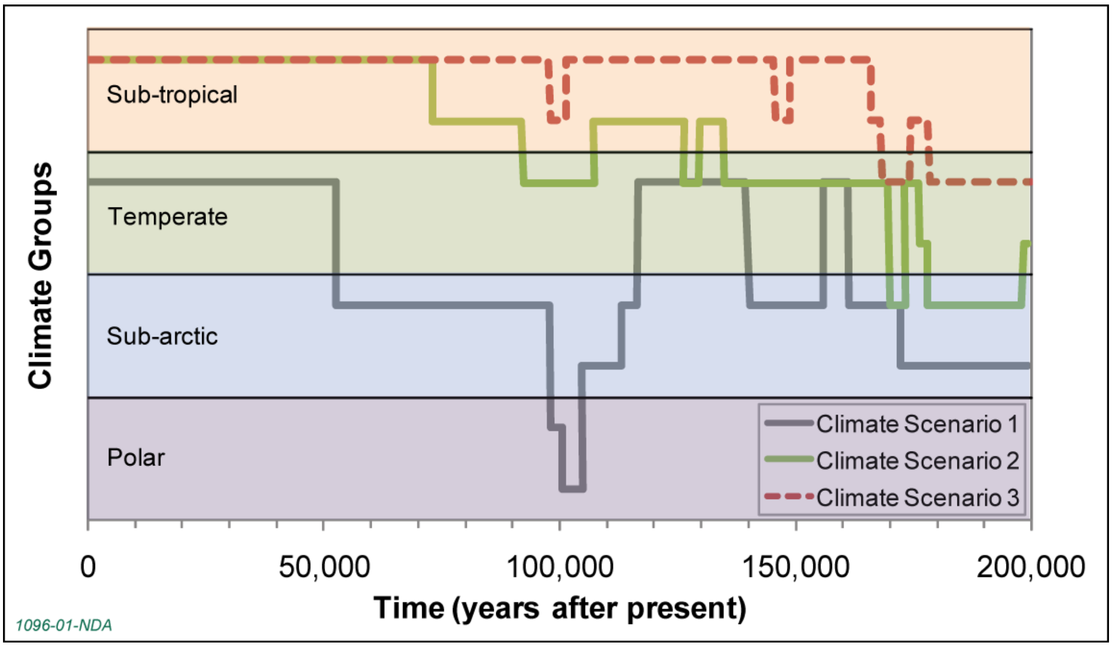
3.2.1 Baseline Climate Scenario (historical levels)

In the absence of further anthropogenic warming, projections indicate that cold-climate conditions would not occur in central England before about 50,000 years after-present and that full glacial conditions would not arise until about 100,000 years after-present.

Figure 11 shows the projected climate states for central England for the three scenarios[10], whereas Figure 12 shows the historical and projected northern hemisphere ice volume for the baseline climate scenario. The figures show that, even under the baseline scenario (which excludes any contribution from fossil fuels beyond the late nineteenth century), the next period of full glacial conditions is not projected to occur for 100,000 years. The lower volume of northern hemisphere ice at that time in comparison with the last glacial maximum about 18,000 years ago strongly suggests that ice-sheet formation in the British Isles would be limited to the north-western upland areas and that lowland Britain would not be glaciated. This view is further supported by the short duration of the projected glacial episode compared with the last glaciation, as there would be only a limited interval available for British ice sheets to develop and spread south from their projected origins in the north-west. Thus, in lowland Britain, polar tundra conditions would be expected to prevail.

[10] These sequences are derived from the output of the MoBidiC model used in BIOCLIM.

Figure 11 Projected climate states for central England for the different scenarios

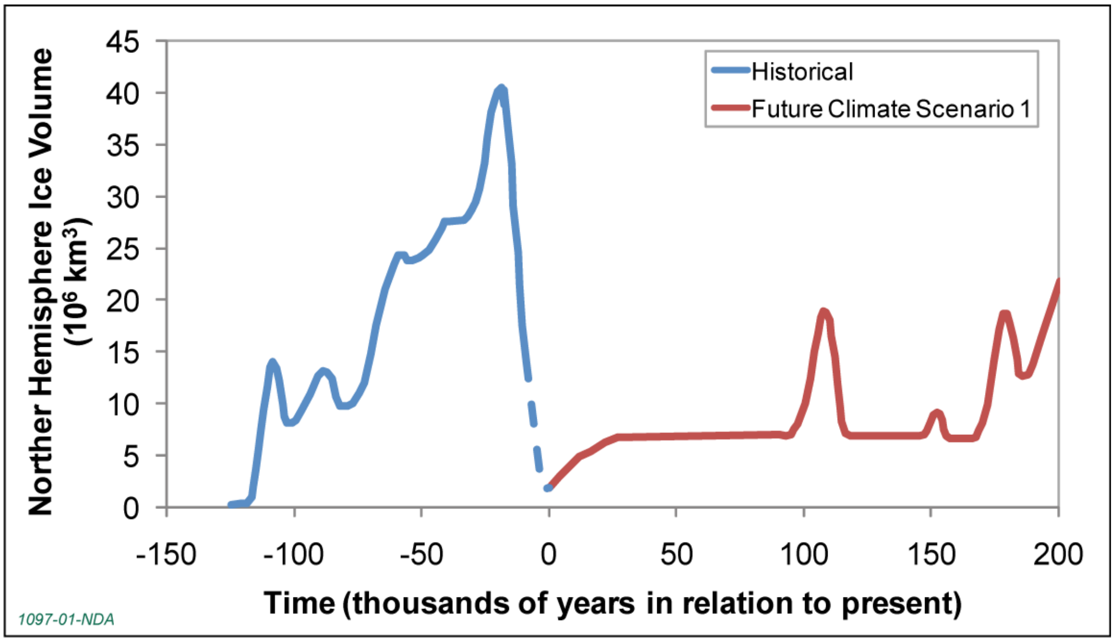


Note: The y-axis represents climate states and is not a linear axis. Step changes indicate when the climate is projected to cross a boundary between one state and the next, such boundaries do not imply step changes in climatic variables such as temperature and precipitation. The representation of transitions between climate states is discussed in Section 4.2. Figure based on [49].

The mean annual temperature of polar tundra conditions is consistent with the development of discontinuous permafrost in central England. This is in accord with evidence from the past, as relict permafrost features are observed from previous glacial episodes. Indeed, it is likely that discontinuous permafrost would begin to develop during the latter part of the preceding sub-arctic climate state [50]. Modelling studies have explored the depth of permafrost that could develop at various locations in Great Britain [51].

Warming from polar tundra conditions is projected to occur somewhat more slowly than at the end of the last glaciation. In that episode, the ice sheets were at their greatest extent about 18,000 years ago and fully interglacial conditions were established in central England 8,000 or 9,000 years later, by the early Holocene. Within that period, substantial oscillations in climate occurred, notably the intensely cold but brief Younger Dryas (of about 1,000 years duration). This was too short to have had a substantial effect on global ice volume, so it is not visible in Figure 12. In the projection, the warming to full interglacial conditions is projected to occur over a period of about 12,000 years. However, this distinction in timing is at the limit of the resolution of the models used.

Figure 12 Modelled historical and projected northern hemisphere ice volume[11] for the baseline climate scenario



Note: Figure based on [47].

[11] Based on results of the MoBidiC model used in BIOCLIM.

3.2.2 Low and High Fossil Fuel Usage Climate Scenarios

The inclusion of additional fossil fuel contributions to global warming within long-term climate projections indicates that warm-climate conditions will persist in central England for about 100,000 years after present, or longer, and that cold-climate conditions will not be encountered until beyond about 170,000 years after present.

Over the next few hundred years the effects of greenhouse-gas releases from fossil fuel combustion are expected to result in a substantial change in the climate of Great Britain. The location of the British Isles, on the margin between oceanic and continental climate domains, and the results of the different downscaling and modelling techniques, imply a relatively rapid transition to cool sub-tropical conditions, see Figure 11. The results imply that overall annual temperatures would be increased by about 2 to 3ºC, without any substantial change in the seasonal cycle and that the total annual precipitation would be very similar to that at the present-day (600 mm [52]), but with a decrease of about 40 mm during the summer months. This implies that the hydrologically effective rainfall (precipitation minus actual evapotranspiration) would be somewhat reduced relative to the present-day, so increasing irrigation requirements.

Overall, it is considered that, following a peak in mean annual temperature over the next few hundred years, a cooling trend will ensue in both the low and high fossil fuel usage scenarios, such that temperate conditions similar to those of the present-day will recur between 90,000 and 170,000 years. Thereafter, there is no strong trend in climate through to 200,000 years, though results for the low fossil fuel usage scenario indicate that a brief cold episode would be expected to occur in around 175,000 years and would persist for a few thousand years.

Beyond 200,000 years, the effects of greenhouse warming due to combustion of fossil fuels would decline to negligible levels. This arises because the long-term component of loss of excess carbon dioxide from the atmosphere occurs as a result of silicate weathering, which has a characteristic timescale of this duration [42]. Simulations undertaken in BIOCLIM covering the period from 200,000 to a million years indicate that glacial-interglacial cycling would persist throughout [44]. Biosphere characteristics subsequent to a major glacial episode would be much more uncertain than those prior to such an episode, even beyond the margin of any ice sheets. Therefore, on time scales beyond 200,000 years, biosphere assessments become even more illustrative and associated calculations are more schematic. Consideration of potential climates up to 200,000 years mean that a broad range of climate states are characterised, from warmer than present-day through to colder climates; these, together with palaeoenvironmental reconstructions of past glacial-interglacial cycles, provide a basis for the more schematic calculations on longer time scales.

3.3 Sea-level changes

The sea-level around the British Isles is projected to increase by approximately 11 to 21 m within the next few thousands of years in response to global climate change. In the far future, sea levels can be expected to fall again as ice sheets increase in size towards future glaciations, falling to tens of metres below the present-day level.

A consequence of global climate change is that it will cause substantial variations in sea level [35].

In projecting overall global sea-level change, consideration needs to be given to the potential contributions from thermal expansion of sea water, the melting of valley glaciers, the melting of the Greenland ice sheet and changes in volume of the Antarctic ice sheets. In the very long-term, glacial episodes are projected to recur, with generation and advance of large ice sheets in the northern hemisphere. The development of these ice sheets will lead to a fall in global sea-level.

There is some regional variation in the degree of sea-level rise because of ocean processes, gravitational effects, and tectonic and isostatic changes [53]. Studies of the significance of thermal expansion and ocean circulation changes indicate that increases around the British Isles are likely to be similar to, or somewhat greater than, the global average. Residual isostatic recovery from the last glaciation will make only a small contribution to future changes in sea level around the British Isles. This contrasts to the situation in Scandinavia where residual isostatic recovery is a major consideration in determining the future development of landscapes adjacent to the Baltic Sea [54].

The implications of the projected changes in global sea-level for the British Isles were considered for the three climate scenarios described in Section 3.2 [35].

The baseline climate scenario was considered in BIOCLIM using two different Global Climate Models. The first indicated a fall in sea-level of about 30 m by the time of peak northern hemisphere ice volumes in about 100,000 years, followed by an increase in sea-level and a secondary fall in around 150,000 years. The second indicated a much smoother development of the northern hemisphere continental ice sheets, but with good agreement on their total volume at the end of the simulation at 200,000 years.

Consideration of the low and high fossil fuel usage climate scenarios showed that sea-levels around the British Isles are likely to rise by about 0.11 to 0.77 m in the short-term (based on [55] and consistent with [56]). More recent conclusions from the IPCC [41] indicate a range of 0.26 to 0.98 m by 2100 AD, depending on the different greenhouse-gas emissions projections. In the medium-term, the rise is expected to be in the range 4 to 12 m, comprising 0.5 to 4.3 m from thermal expansion [55], 0.5 m from the loss of valley glaciers, 3 to 6 m from the Greenland ice sheet [55, 57] and, possibly, ~1 m from the West Antarctic Ice Sheet, with the East Antarctic Ice Sheet approximately in balance or even slightly increasing in volume. Sea-levels are then expected to be maintained at levels about 11 to 21 m above the present-day position, depending on the long-term stability of the West Antarctic Ice Sheet [55, 57, 58], until about 170,000 years from now. Beyond that time, a decrease in level to the present-day value or a few metres below it seems likely to occur. These estimates are summarised in Table 4.

Table 4 Estimates of sea-level rise for the British Isles

Period	Lower estimate	Upper-estimate
Short-term – hundred years	0.26 m	0.98 m
Medium-term – hundreds of years	4 m	12 m
Long-term – thousands of years	11 m	21 m

It is recognised that there are considerable uncertainties associated with these longer-term projections. The IPCC [41] evaluation, with a low degree of confidence, is that a sea-level rise of 1 to 3 m per degree of global warming is projected if the warming is sustained for several millennia. However, at a medium level of confidence, the IPCC concludes that a global warming of two to four degrees above the pre-industrial baseline would lead to almost complete loss of the Greenland ice sheet over a millennium or more, with a corresponding global sea-level rise of about 7 m.

3.4 Landscape evolution

The way in which our understanding of how the landscape will develop is consistent with climate projections, focusing on an inland, lowland context. Extensive agricultural usage remains viable throughout the projected warm and temperate periods. Boreal and subsequent periglacial landscapes will eventually develop as the Earth's climate cools towards the next glaciation.

Various landscape evolution scenarios have been developed for the British Isles, focusing on lowland landscapes. The landscape evolution scenarios are based on the low and high fossil fuel usage scenarios discussed above and a consideration of the processes described in Table 5 [25, 35]. The baseline climate scenario, which excludes additional contributions from fossil fuel usage beyond the late nineteenth century, is unfeasible and is not carried forward. Variant scenarios in which global warming is mitigated or even reversed through anthropogenic interventions (e.g. geoengineering) are not explicitly included in our assessments, at present, but the viability of such scenarios and their likelihood of implementation are continually under review. Discussion of landscape evolution focuses on inland contexts; consideration of potential releases in a coastal context is given in Section 5.

Projected sequences of climate and landscape change to 250 ka after present for the low and high fossil fuel usage scenarios are summarised in Table 6 and Table 7, based on [25]. Beyond 250 ka after present, the sequences merge and a projected sequence is shown in Table 8 [25]. The warm humid conditions are broadly those experienced today in SW France, NW Spain and northern Portugal and the semi-arid conditions are broadly consistent with climate conditions experienced today in the Mediterranean region, so there is no reason to suppose that the extensive agricultural usage of the landscape observed at the present-day would be abandoned. The illustrations are based on medium-sized catchments, which are in the range 10-100 km^2; for comparison, small catchments are in the range from less than 1 km^2 to 10 km^2 and large catchments exceed 100 km^2.

Table 5 Landscape evolution processes

Process	Description
Erosion	Weathering of the land surface and subsequent removal of solids under the influence of gravity, wind and water. Erosion results in lowering of the land surface (denudation). It includes specific types of erosion, such as that caused by rivers and streams (fluvial erosion), which results in their incision (down-cutting) into a landform. Under glacial conditions, substantial transport of unconsolidated surface deposits occurs extensively during ice-sheet advance, with subsequent erosion of the underlying bedrock giving rise to new glacial deposits. At some locations, glacial erosion can lead to extensive remodelling and deepening of pre-existing valleys ('glacial scouring').
Sedimentation/ Deposition	Deposition of eroded material such that material is added to the landform.
Tectonic movements, including isostacy	Movement in the Earth's tectonic plates, which can result in changes in elevation. The relative geological stability of the British Isles means that seismic events, such as earthquakes, are of limited significance. However, other tectonic movements are relevant, notably isostacy, by which the elevation of the land is affected by glacial loading and subsequent rebound/uplift [33].

Table 6 Projected landscape evolution for a medium-sized catchment over the next 250 ka under the low fossil fuel usage scenario

Period	Illustration	State & Notes
0 to 90 ka		**Sub-tropical (warm humid):** Susceptible to erosion, but stable under good land management; a long period of erosion and aggregation of fine sediments in the valley bottoms progressively reduces relief; water is scarce in the summer and is managed for farming, including irrigation.
90 to 170 ka		**Temperate:** Predominantly agricultural; denudation reduces relief slowly over time; long-term isostatic adjustment.
170 to 250 ka		**Boreal:** Incision in the upper catchment; aggregation of coarser deposits in the valley floor; continued isostatic adjustment.

Note: The illustrative sequence for low and high fossil fuel usage scenarios merge after 250 ka, so a single sequence beyond 250 ka is shown in Table 8.

Table 7 Projected landscape evolution for a medium-sized catchment over the next 250 ka under the high fossil fuel usage scenario

Period	Illustration	State & Notes
0 to 170 ka		**Sub-tropical (semi-arid):** Susceptible to erosion, but stable under good land management; a long period of erosion and aggregation of fine sediments in the valley bottom progressively reduces relief; water is scarce and is managed for farming, including irrigation.
170 to 250 ka		**Temperate:** Catchment relief may have been reduced by half by this time; fertile soils in the valley floors intensively farmed.

Note: The illustrative sequence for low and high fossil fuel usage scenarios merge after 250 ka, so a single sequence beyond 250 ka is shown in Table 8.

Table 8 Projected landscape evolution for a medium-sized catchment beyond 250 ka for both the low and high fossil fuel usage scenario

Period	Illustration	State & Notes
250 to 310 ka		**Boreal:** Further incision in the upper catchment and aggregation of coarser deposits in the valley floor; continued isostatic adjustment.
310 to 335 ka		**Periglacial:** Further incision and aggregation of coarser sediments; continued isostatic adjustment; likely to be extensive hunting and herding activities.
335 to 354 ka		**Glacial:** Potential for glacial scouring, along with further incision and aggregation of coarser sediments; continued isostatic adjustment; unlikely to be permanent human occupancy.
354 to 357 ka		**Periglacial:** Further incision and aggregation of coarser sediments; continued isostatic adjustment; likely to be extensive hunting and herding activities.
357 to 360 ka		**Boreal:** Further incision in the upper catchment and aggregation of coarser deposits in the valley floor; continued isostatic adjustment.
360 to 370 ka		**Temperate:** Return to gradual denudation; finer sediments accumulate over the coarser deposits in the valley floor; gradual increase in catchment size.

Note: The illustrative sequence for low and high fossil fuel usage scenarios merge after 250 ka, such that the sequence from 250 ka illustrated in Table 8 follows both that shown in Table 6 and that shown in Table 7.

4 Biosphere descriptions

This section describes how projections of long-term climate and landscape evolution are used to develop descriptions of the biosphere at a sufficient level of detail to support their use in the safety case. The principal focus on potential releases to terrestrial systems is justified (Section 4.1), followed by a description of how the biosphere is considered as a sequence of states and transitions between those states (Section 4.2). The way in which potential contaminant transport and exposure in the biosphere is conceptualised is described (Section 4.3), together with specific consideration of near-surface hydrogeology (Section 4.4), gaseous releases to the biosphere (Section 4.5) and potentially exposed groups (Section 4.6).

4.1 Principal focus on terrestrial/freshwater systems

Our principal focus is given to potential releases to terrestrial/freshwater systems, based on the additional dilution that typically occurs with contaminant releases to estuarine, coastal and marine systems.

The main emphasis of long-term assessments is the evaluation of the impacts of discharges of contaminants to terrestrial and freshwater systems. A focus on terrestrial and freshwater systems is also reflected in international collaborative projects relating to the biosphere [24, 59]. Assessment calculations undertaken in the late 1980s demonstrated that radiological impacts of discharges to terrestrial and freshwater environments were larger than those to marine environments, largely due to the much higher degree of dilution associated with marine environments that more than compensates for high bioaccumulation factors for some radionuclides in marine organisms [60, 61]. RWM's post-closure biosphere assessment capability has been updated to include potential releases to estuarine, coastal and marine systems around the UK [62], as described in Section 5.1.2. This helps to justify a principal focus on releases to terrestrial and freshwater systems, but also allows potential impacts associated with releases to these other biosphere systems to be evaluated, which will be of interest should coastal locations be identified through the site selection process. Studies undertaken using this augmented capability confirm that potential radiological impacts are generally substantially larger for discharges to terrestrial and freshwater environments than for corresponding discharges to estuarine, coastal and marine environments. Future sensitivity calculations will explore the robustness of the comparison, along with potential implications of climate change on models for estuarine, coastal and marine systems, identifying controlling characteristics and processes[12].

[12] Task 002 of the Science and Technology Plan for Geological Disposal [10].

4.2 Biosphere system states and transitions

Climate and landscape narratives are interpreted as sequences of biosphere states and transitions. However, at this generic stage, the level of detail needed to represent evolving systems is not available, so the biosphere systems are represented as a series of independent states.

Before developing descriptions of the biosphere systems to be assessed, it is necessary to consider whether the radiological assessment should explicitly represent environmental change as a gradual process of development (the sequential approach) or as a series of independent biosphere states (the non-sequential approach). It is accepted that there will be substantial environmental change on the long timescales of relevance to post-closure studies. However, whether the biosphere should be represented as a series of independent states or as a sequentially evolving system depends on whether that change is occurring at the time of potential radionuclide releases.

As illustrated in Section 3.4, it is possible to construct continuous narratives of climate and landscape change for the British Isles. Although there are extended periods within those scenarios in which the climate and landscape change only slowly there are also periods, for example warming from a glacial episode, over which environmental change is relatively rapid. Furthermore, there is the potential for climate and landscape states to persist for only a few thousand years. In these circumstances, the non-sequential approach is not thought to be adequate to address all the issues that arise, including potential for accumulation and subsequent remobilisation of radionuclides released to the biosphere.

Due to the projected pattern of insolation and anthropogenically enhanced greenhouse gas emissions, the present interglacial period is expected to extend to 170 ka after present or longer (see Section 3.2). Warm climate conditions are anticipated to persist throughout much of this period so that environmental changes driven by climate are not expected to be significant beyond an initial warming phase. For inland lowland sites, there are projected to be no well-marked transitions between biosphere states during this stage [63], such that explicit representation of environmental change within the biosphere models is not justified. Significant environmental change may occur at some sites, for example if a low-lying coastal location is considered. However, the absence of a specific site or sites at the current stage of the GDF site selection process means that the level of detail required to represent an evolving system is not available. Therefore, the biosphere models for potential releases to terrestrial and freshwater systems [25] and to estuarine, coastal and marine systems adopt [62] a non-sequential approach.

4.3 Conceptualisation of the biosphere

Conceptualisations of contaminant transport and potential impacts are developed on the basis of the descriptions of long-term climate and landscape evolution. Interaction matrices provide a good framework for developing conceptual models.

Descriptions of biosphere systems, along with consideration of the way in which environmental change should be represented, allow conceptual models for contaminant transport, and potential impacts, to be developed. Once potential sites are identified, such descriptions will draw on characterisation of the present-day biosphere both at those sites, but also, potentially, at sites analogous of future conditions that might reasonably be expected [28], based on assessment of climate and landscape change described above. Also, prior to site selection, site-specific data from locations other than candidate sites may be useful for developing and testing models that are subsequently to be used in a site-specific context.

Interaction matrices are used as a tool to define the conceptualisation of FEPs for contaminant migration and exposure, underpinning the development of an associated mathematical model (see Figure 13). The leading diagonal elements of the interaction matrices represent principal features of the biosphere. The processes that operate between them are considered in the off-diagonal elements. Use of this type of interaction matrix for characterising the biosphere transport of radionuclides has been made by the IAEA within BIOMASS [24], within the EU-funded BIOCLIM project [59], and the concept has been further developed by the International Union of Radioecologists (IUR) [64, see also 65] and, in the context of the geosphere-biosphere interface, by BIOPROTA[13] [66].

This approach is used to characterise biosphere system states in light of the climate and landscape evolution scenarios described in Sections 3.2 and 3.4 above [35]. The scenarios are characterised in terms of a sequence of states for which descriptions are developed. Interaction matrices are also used to characterise contaminant migration and exposure following potential releases to estuarine, coastal and marine biosphere systems [62].

4.4 Hydrology and near-surface hydrogeology

For contaminant releases in groundwater, near-surface hydrogeology and catchment-scale hydrology are important factors in determining the degree of dilution of deeper groundwaters as they reach the near-surface, as well as defining potential discharge locations and characteristics.

Radionuclides entering the biosphere in groundwater are primarily transported in surface waters and near-surface groundwaters. Therefore, hydrological and hydrogeological understanding and modelling make an important contribution to studies of radionuclide transport in the biosphere. Specifically, an important component of the biosphere system for the groundwater pathway is the region in which deeper, potentially contaminated groundwater disperses into more recent groundwater in the shallow part of the system prior to release to the surface, either via wells or via natural groundwater discharge [32]. The near-surface hydrological system is illustrated in Figure 14 and it has been explored in detail in the BIOPROTA geosphere-biosphere interface project, in which a detailed methodology has been developed for its characterisation [32, 66].

The discussion in Section 3.2 indicates that the present-day interglacial period could extend well beyond 100,000 years into the future. This increases the relevance of understanding the present-day system to informing assumptions adopted over such long timescales. Specifically, process-based hydrological modelling can be used to synthesise detailed information that will be generated through site characterisation studies to help inform and justify a characterisation of that environment suitable for assessment calculations [31]. The underlying, detailed and process-based models cannot provide more accurate projections of the future; however, they do provide confidence in the plausibility and internal consistency of the assumptions adopted [15, 67].

[13] Task 001 of the Science and Technology Plan for Geological Disposal [10].

Figure 13 Generic interaction matrix for radionuclide migration and exposure in inland terrestrial biospheres (from [25])

Interface with Geosphere	Discharge Diffusion		Irrigation		Spray Degassing	Interception	Ingestion	Ingestion Bathing	
Recharge Diffusion	**Near-surface Aquifer**	Water advection Diffusion	Irrigation	Discharge	Spray Degassing	Interception	Ingestion	Ingestion Bathing	Water advection
	Recharge Diffusion	**Sub-soil**	Water advection Diffusion Bioturbation	Seepage/ Through-flow Erosion		Root uptake			
		Infiltration Diffusion Bioturbation	**Surface soil**	Seepage/ Through-flow	Suspension (dust) Degassing	Root uptake External contamination	Ingestion	Ingestion External irradiation	
	Recharge		Irrigation Infiltration	**Surface water**	Evaporation Gas evolution Spray	Interception	Ingestion Uptake (by fish)	Ingestion Bathing	Water advection
			Deposition Diffusion	Deposition	**Atmosphere**	Deposition Photosynthesis	Inhalation	Inhalation Immersion	Air flow
		Root exudation Root respiration Senescence Death	Root exudation Root respiration Senescence Death		Transpiration Respiration	**Vegetation**	Ingestion	Ingestion	Cropping
			Excretion Death	Excretion Death	Exhalation Eructation	Excretion Death	**Animals**	Ingestion	Produce
			Excretion	Excretion	Exhalation			**Humans**	
									Elsewhere

Key: Components of the biosphere in lead-diagonal elements (green); Potentially significant interactions in off-diagonal elements and highlighted in blue; Absence of potentially significant interactions in blank elements

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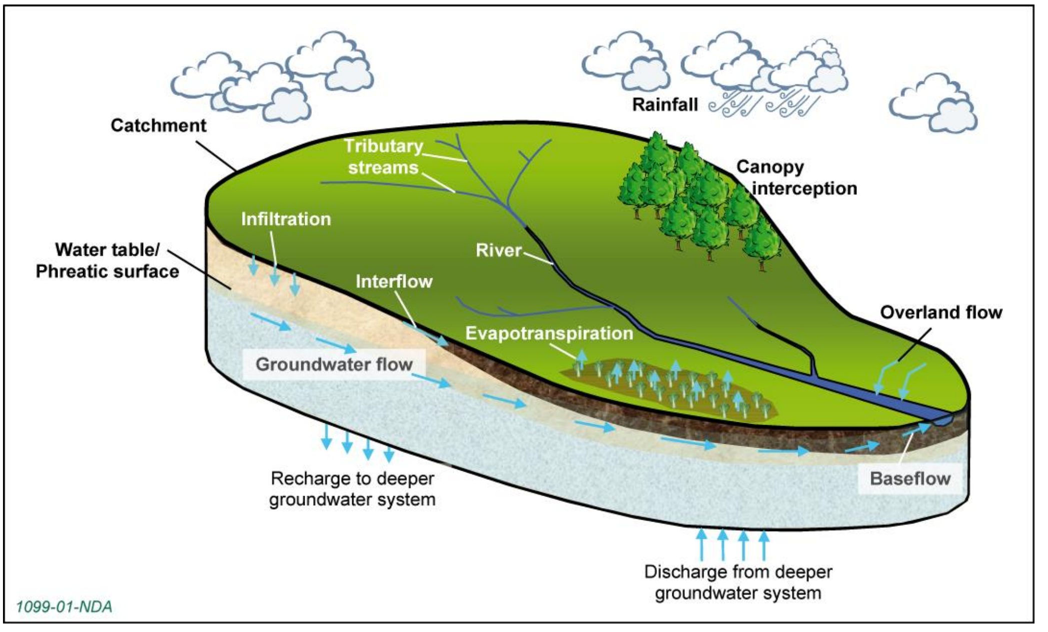
Figure 14 Near-surface hydrological system



Process-based catchment-scale modelling tools can be used from desk-based studies through to development of detailed models in support of site-specific safety studies and can also be used to demonstrate understanding of a site in support of the EIA. However, sufficient data might not be available at the early stages of site characterisation to warrant building a process-based model, therefore a simpler approach may initially be appropriate in order to obtain an understanding of the hydrological environment, key hydrological processes and the water balance.

In this sub-section, emphasis is placed on the role of catchment-scale hydrological modelling for determining the near-surface dilution and distribution of contaminants in the biosphere subsequent to their release from a geological disposal facility, whilst the potential role of such modelling in setting boundary conditions for the deep groundwater system should be kept in mind, particularly as the programme moves towards site-specific studies. The spatial scale and location for hydrological modelling that are required to support regional-scale groundwater understanding may differ from that needed to support understanding of the dilution and distribution of potential discharges to the biosphere.

Reviews of the various process-based modelling approaches have been undertaken, with a view to determining the approach to be used in support of future assessment studies [35, 68]. Two modelling codes, MIKE SHE [69] and SHETRAN [70], are the only fully integrated process-based, spatially distributed catchment models, incorporating a true groundwater flow model, simulating all components of the catchment water balance. Both are also able to simulate contaminant transport, which enables comparison against assessment-level representations and/or against tracer studies.

As required, further work will be undertaken to compare the capabilities of SHETRAN and MIKE SHE to determine if and how these tools should be used in support of future studies. It is possible that both tools will be used for different purposes, and/or that work will be commissioned to enhance the capabilities of one or other of these modelling systems to adapt it better to the various requirements that are foreseen in this area. In this context, it is noted that a new generation of software systems in which hydrogeological and hydrogeochemical representations are closely coupled may replace or complement existing approaches to modelling contaminant transport in surface and near-surface hydrological and hydrogeological systems [66].

4.5 Gaseous release to the biosphere

For the gas pathway attention is focussed on ^{14}C, as it is the only radionuclide relevant to the gas pathway with a sufficient half-life to be of interest on post-closure timescales. ^{14}C would principally be released from the GDF as methane.

In the case of releases of radioactive gases to the biosphere, the main radionuclides of potential interest are tritium and ^{14}C [5]. Although it is considered within the operational environmental safety assessment [71], the half-life of tritium is sufficiently short that it will generally be of little relevance to the estimation of post-closure radiological impacts [72]. Therefore, attention is appropriately focused on ^{14}C, which may be released from the GDF incorporated in carbon dioxide or methane and possibly, to some degree, as other gases such as carbon monoxide, ethylene, ethane and acetylene. In practice, ^{14}C initially present in carbon dioxide is likely to be largely taken up in the engineered system through carbonation reactions with cementitious materials, so the focus in the biosphere context is on methane. Methane can be converted to carbon dioxide in the soil [73]. This is an important process because carbon dioxide is taken-up by plants and incorporated into organic matter and thence the food-chain, whereas methane is not. Research and modelling relating to gaseous release of ^{14}C to the biosphere is described in Section 5.2.2.

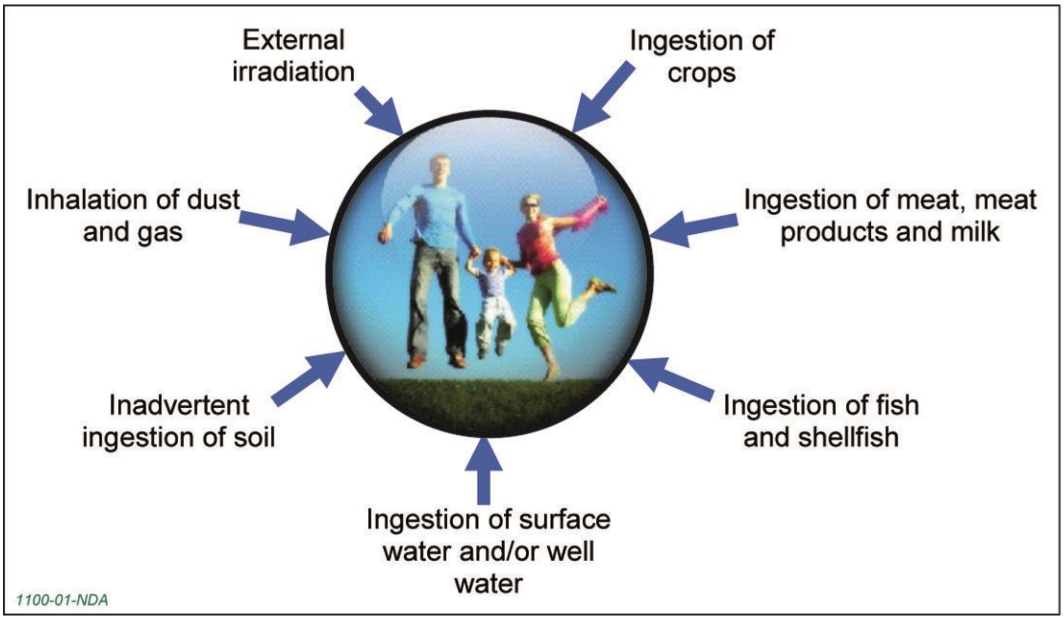
4.6 Potentially exposed groups

Potential doses to humans remain a primary focus of radiological assessments. Exposures via external irradiation, ingestion and inhalation are considered, with generic potentially exposed groups being defined that make maximal use of local, potentially contaminated, resources.

To perform human dose calculations, it is necessary to complement descriptions of the biosphere system with information on the habits and behaviour of people assumed to make use of the contaminated area of the biosphere. In operational assessments (related to the present-day), use is made of the concept of the representative member of a critical group. The critical group comprises a reasonably homogeneous subset of the population likely to receive the highest exposures and is characterised by habits data representing high percentiles of occupancy and consumption. In the context of post-closure biosphere studies (and consistent with the regulatory guidance summarised in Box 1), the concept of a critical group is replaced by the concept of a potentially exposed group (PEG), characterised by more generic habits data due to uncertainties in predicting future behaviour.

It is assumed that all members of the PEGs considered live in the area where the highest radionuclide concentrations are calculated; Figure 15 illustrates the exposure pathways considered. Calculations focus on potential exposure of adults, however, the sensitivity of the biosphere dose conversion factors to consideration of different age groups is discussed in Section 5.1.4.

Figure 15 Exposure pathways considered for ionising radiation



PEG characteristics are primarily defined based on generalised habits data [74] and include consideration of:

- consumption rates for plant produce, including domestic fruit, vegetables, cereals and plants foraged from coastal areas
- consumption rates for animal produce, including meat, liver, kidney, milk and milk products (for example cheese), including animals grazed on salt-marsh in a coastal context
- consumption rates for freshwater and marine fish, crustaceans, molluscs and laverbread (a form of processed seaweed) for the coastal community
- inadvertent ingestion of soil
- water intake
- indoor and outdoor occupancy.

Consideration is given to PEG characteristics for temperate, sub-tropical, boreal and tundra climate states. However, beyond special considerations relating to the low primary productivity of tundra conditions, it is considered that it would be over-refinement of the analysis to make significant distinctions from the temperate characteristics for the purposes of radiological assessment. It is not possible to identify which food groups might dominate potential exposures prior to undertaking calculations. Therefore, it is appropriate and cautious to adopt high consumption rates across all food groups. Should ingestion of plant and/or animal produce result in calculated exposures being at or close to the risk criterion, then it is appropriate to undertake a more realistic calculation in which only two food groups are represented at the high intake rates, consistent with guidance in [35] and [75]. Whilst the National Dose Assessment Working Group (NDAWG) guidance relates to identification of critical group habits in the context of operational assessments, the principles remain valid for a post-closure context.

Consideration of habit data adopted for radiological assessment purposes in different European countries from Sweden to Spain shows that differences between the values used seem more to reflect variations in local practices and assumptions than climatically related differences [35]. It is therefore reasonable to adopt the same dietary habits for PEGs under the different climate conditions considered for stylised assessment calculations representing releases to terrestrial and freshwater systems.

The area required for a modern smallholding supporting several head of cattle is 4 to 12 hectares [76], which is very similar to the area used by a single family in the context of medieval farming [76, 77], indicating a degree of independence of the details of farming practice. This implies an order-of-magnitude area of 10 km^2 would be required for a village of about 300 people, which was adopted as a basis for previous assessments [61].

5 Representation of the biosphere

RWM's understanding of the biosphere is ultimately reflected in the quantitative assessments needed to evaluate potential impacts for comparison against regulatory criteria. This section presents the representation of the biosphere used by RWM. The representation of terrestrial, estuarine, coastal and marine biosphere systems is described (Section 5.1). Key radionuclides for post-closure safety are identified (Section 5.2), non-radiological species are discussed (Section 5.3), along with potential impacts on wildlife (Section 5.4).

5.1 Biosphere model

Models for potential groundwater releases to terrestrial, freshwater, estuarine, coastal and marine systems have been developed. These are used to calculate biosphere dose conversion factors, which are applied to calculated radionuclide release rates from the geosphere in assessment models.

The mathematical model of the biosphere developed on the basis of the considerations set out in previous sections comprises two major components, representing: (i) the terrestrial plus freshwater aspects and (ii) the estuarine plus marine aspects, respectively. The two components are coupled and implemented within the GoldSim [78] simulation software. The way in which each component is represented is summarised in the sub-sections below; detailed accounts of the conceptual and mathematic bases and of their software implementation are provided elsewhere [25, 62].

The biosphere model has also been adapted for calculating concentrations of non-radiological species in environmental media, so that potential impacts on human health and the environment of the release of non-radiological species from the GDF can also be evaluated, as discussed in Section 5.3.

5.1.1 Representation of terrestrial and freshwater systems

A lowland terrestrial and freshwater system is represented, with potential contamination via irrigation and groundwater discharge. The area is taken to be uniformly contaminated and used by a self-sufficient exposure group.

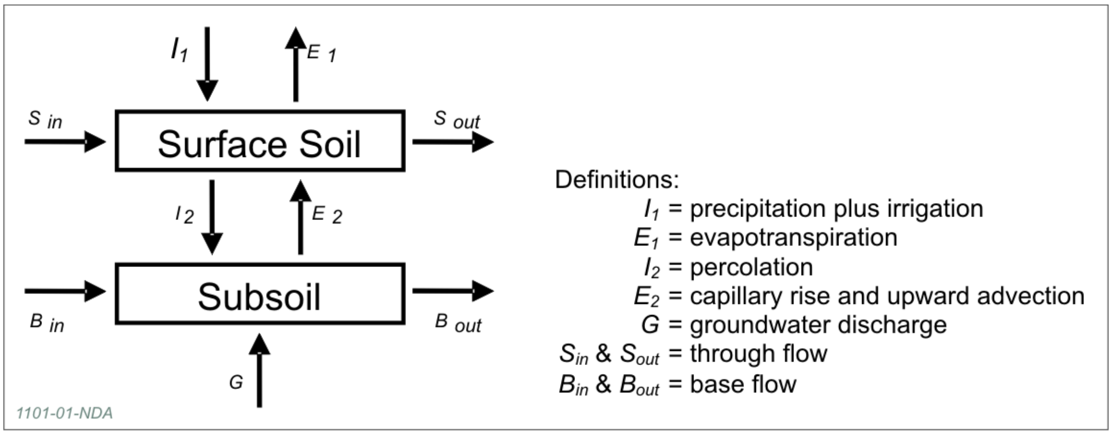
For generic performance studies, a biosphere model is used that assumes contaminants are uniformly distributed over the terrestrial area used by the potentially exposed groups, consistent with the aim of keeping the approach as simple as can be justified, erring on the side of caution. The area used is determined by consideration both of the resource requirements of the potentially exposed groups and by the projected dispersion of radionuclides released to groundwater, as determined in other components of the modelling of the disposal system. A discussion of the discharge areas and near-surface aquifer flow rates for calculations supporting the DSSC is given in the Data Report [9]. A landscape modelling approach that represents spatial variation in contaminant concentrations has been adopted by SKB and Posiva[14] in their safety cases [79, 80]. However, this is in the context of specific sites that have been extensively studied in field-

[14] SKB and Posiva Oy are the organisations responsible for radioactive waste disposal in Sweden and Finland, respectively.

based characterisation programmes. Also, the Swedish and Finnish regulatory requirements focus particular interest on the next few thousand years, over which time post-glacial uplift and associated shoreline displacement will be a major factor in changing biosphere characteristics [81, 82].

The terrestrial and freshwater component of the biosphere model (see Box 3) is based on the assumption that water-mediated transport of contaminants dominates over solid-based transport and uses a two-layer representation of the soil zone, including both a surface-soil layer and a subsoil layer (Figure 16). The soil is defined in terms of its hydrological characteristics. Precipitation and irrigation inputs are to the surface soil layer and evapotranspiration losses are also from that layer. Groundwater discharge occurs to the lower soil layer. Upward and downward flows between the layers represent time-averaged advective fluxes over periods of wetting and drying of the soil column. Sub-horizontal throughflow and baseflow are also included, but, in practice, water fluxes from upslope are neglected; as any such fluxes would tend to result in decreases in contaminant concentrations in the soil, so only throughflow and baseflow generated in the model area are included and are directed downslope. This is consistent with the approach of erring on the side of caution. Values of the various hydrological parameters are set to correspond to the observed characteristics of the various Hydrology of Soil Types (HOST) classes adopted in the British Isles ([83], see also [84]), whilst reference calculations are undertaken for a well-drained loam, as is appropriate for a large proportion of agricultural land and in the context of domestic cultivation.

Figure 16 Representation of the soil system in the biosphere model



The model represents a range of climate conditions that are projected to be relevant to lowland Britain in the next few hundred thousand years (as discussed in Section 3.2). The hydrological characteristics of the model draw on analyses of data from European climatological stations taken to be analogous to conditions in central England under the different climate states. The data include monthly temperature (see Figure 17) and precipitation, which are used to support plausible values of evapotranspiration, soil moisture status and, in turn, estimated irrigation requirements for each climate state. The use of analogue data helps to ensure internal consistency in the representation of each climate state, recognising that the results remain stylised projections of future conditions.

The conceptual model for contaminant transport in the terrestrial and freshwater environments is illustrated in Figure 18.

Box 3 Potential releases to terrestrial and freshwater systems

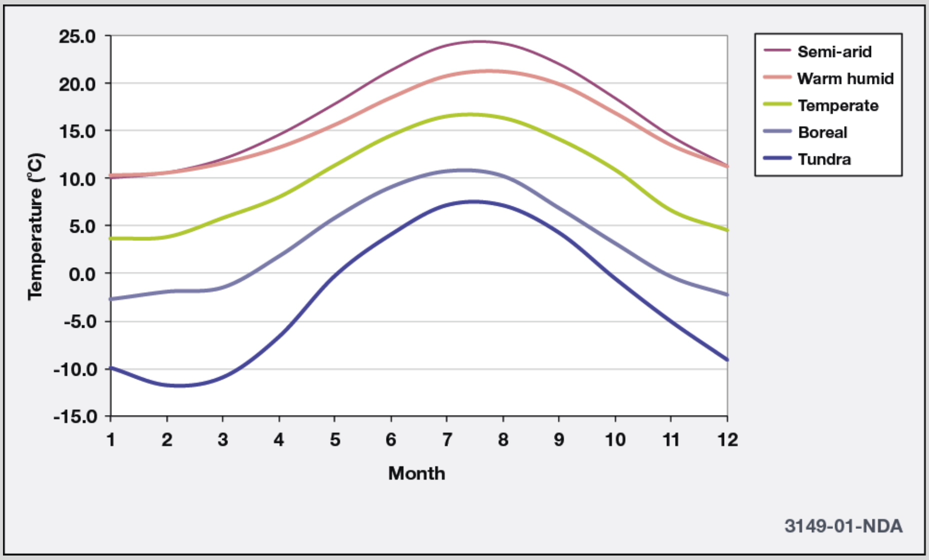
Our approach to calculating potential doses associated with radionuclide releases in groundwater to terrestrial and freshwater biosphere systems was updated in 2011 [85]. The main developments included in the update are listed below:

- biosphere studies in support of geological disposal in the UK provided a key input to the development of the IAEA BIOMASS methodology [24]; the documentation and justification of RWM's approach to the biosphere was updated and presented in a manner that is consistent with that methodology
- similarly, biosphere studies in support of geological disposal in the UK provided a key input to the work undertaken within the EC BIOCLIM project [59]; the updated approach draws directly on the BIOCLIM work to justify explicit representation of present-day, warmer, boreal and periglacial climate states (as opposed to solely representing a present-day temperate system, as had been the case previously).

The current long interglacial period, coupled with the absence of a specific site and increasing uncertainties on longer timescales mean that each of the climate states is represented independent of the others (adopting a non-sequential representation using BIOMASS and BIOCLIM terminology, see discussion in Section 4.2).

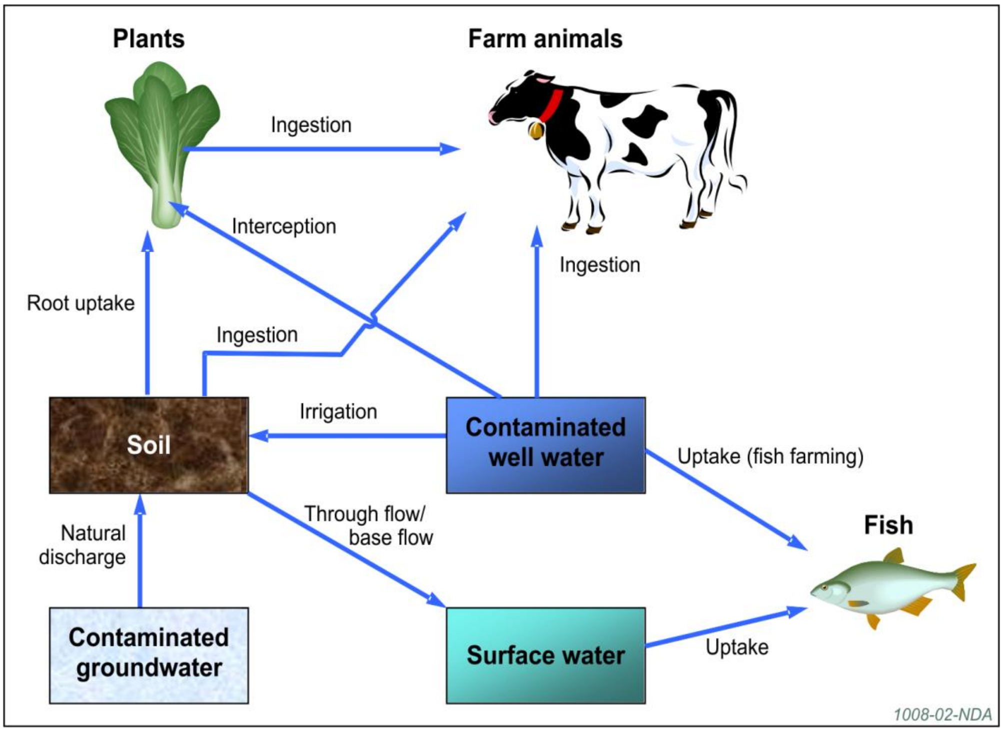
The updated model uses the analogue data compiled within the BIOCLIM project to support parameterisation of each of the climate states, as illustrated in Figure 17. Other biosphere parameters were updated for consistency with the Environmental Safety Case for the LLWR [86] which, in turn, drew on work supporting the latest international recommendations, subsequently reflected in [87].

Figure 17 Average monthly temperatures for the different climate states, based on analogue climate stations [25]



Consistent with other aspects of post-closure safety case modelling, the updated biosphere model was implemented in GoldSim, a change from the spreadsheet implementation adopted previously. The report describing the model for releases to terrestrial and freshwater systems was updated in 2013 [25] to cross-reference to the work on calculation of potential releases to estuarine, coastal and marine biosphere systems.

Figure 18 Contaminant transport processes considered for release to a temperate terrestrial biosphere via the groundwater pathway



Note: The figure indicates whether the underlying model for each process is dynamic, or whether equilibrium assumptions are adopted.

General data used with the terrestrial and freshwater component of the model are given in [25]. The model also requires substantial datasets of radionuclide-specific and element-specific data. Radionuclide-specific data relate to radioactive decay characteristics, factors relating intakes of radionuclides by ingestion and inhalation to committed effective doses and dose factors for external irradiation. Element-specific data relate to sorption to soils, concentration ratios for plants relative to soils, transfer factors to animal products relative to their intakes, concentration factors for freshwater fish relative to their surrounding water, and various translocation factors between spray irrigation and edible crops. These are also discussed in [25]. Similar studies are also taking place as part of the NERC TREE programme. Deterministic sensitivity analyses are used to investigate the effects of parameter uncertainty, see Section 5.1.4.

The radionuclide-specific decay data and dose coefficients are either relatively well defined or are taken from internationally accepted sources and, as such, are taken to be relatively well characterised (for example [88]). Considerable uncertainty can surround element-dependent data, including sorption coefficients (K_d), soil-to-plant concentration ratios and transfer factors to plant and animal produce. The model includes consideration of the latest authoritative international references [87] and the results of 20 years of experimental studies at Imperial College relating to key radionuclides relevant to geological disposal [89].

5.1.2 Representation of estuarine, coastal and marine systems

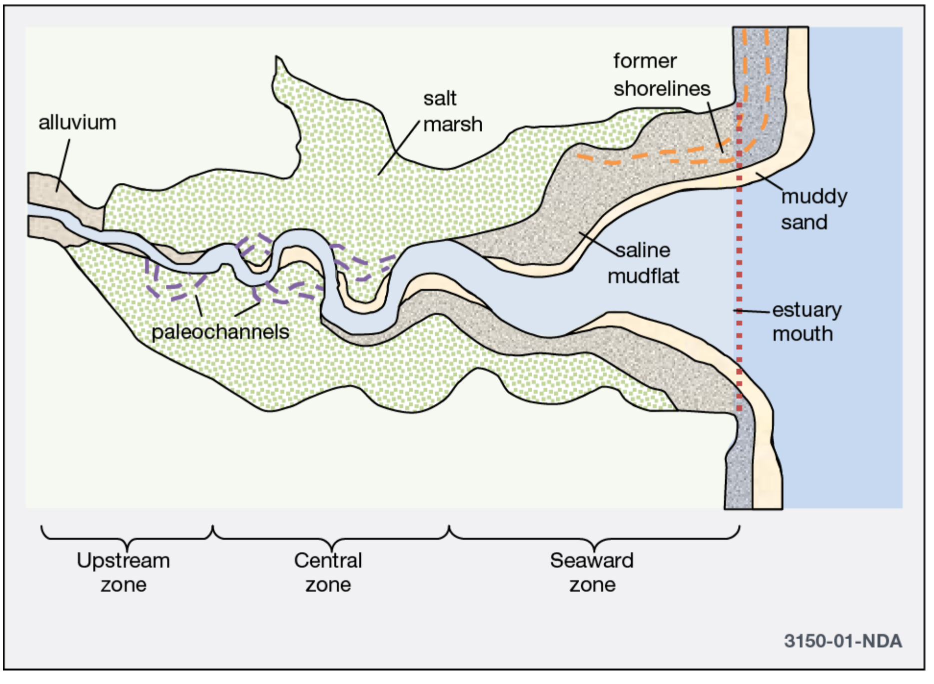
Potential releases to estuarine, coastal and marine systems are represented. Both occupational and recreational exposure groups are considered that make maximal use of the potentially contaminated areas.

The conceptual basis of the estuarine and marine component of the biosphere model [62] is that radionuclides can enter estuarine, coastal and marine systems either directly in groundwater or in freshwater discharges. Although larger rivers typically enter the sea through estuaries, this is not the case for smaller rivers and streams, or where the boundary with the marine environment has been substantially modified by human actions (for example through the construction of harbours). Furthermore, both surface and subsurface runoff from the terrestrial environment may enter the coastal environment directly (for example in springs or seeps) rather than in channel flow.

In the current model (see also Box 4), the generic coastal and marine biosphere system comprises an estuary (which may or may not be present), a coastal environment (stretching from the cliff line to the low water mark to encompass the storm beach, if present, and the foreshore), and a marine environment comprising both near-shore and offshore components. A spatially distributed representation is appropriate to capture both the internal structures of the biosphere components and the implicit geometric relationships between them. This is in contrast to the current terrestrial biosphere model, which is applied to assumed spatially uniform agricultural ecosystems, for which a point-scale representation is appropriate [25].

Where estuaries are present, they can be complex systems, including channels, bare areas of sediment, sediments stabilised by vegetation and salt marshes (see Figure 19). The detailed configuration of these various components changes rather rapidly, on timescales ranging from that of the tidal cycle to channel alteration over hundreds of years, and the overall estuarine configuration is fundamentally transient, being governed by factors such as sea-level, sediment supply and human activities (for example dredging).

Figure 19: Characteristics of a tide-dominated estuary (adapted from [90])



Box 4 Potential releases to estuarine, coastal and marine systems

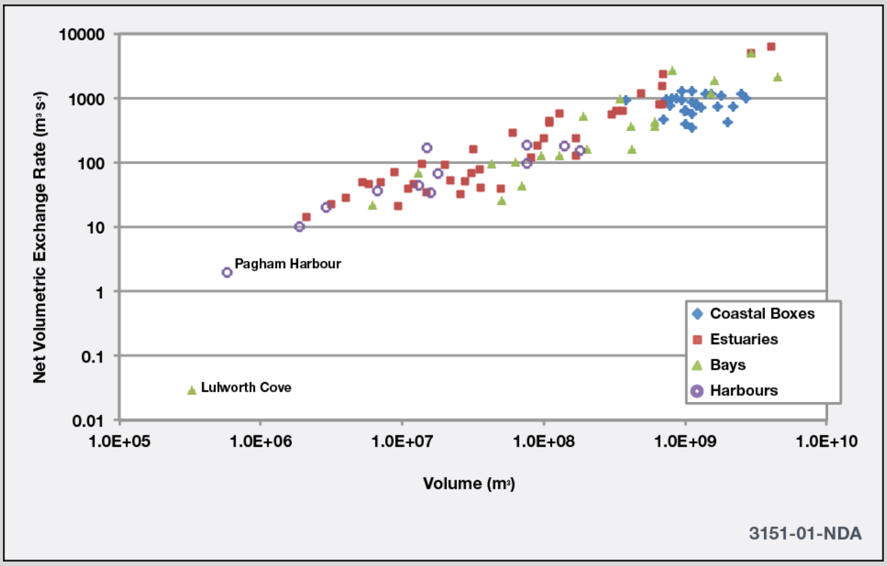
Previous safety cases for geological disposal (for example [91]) have concentrated on assessing the potential impact of radionuclide releases to terrestrial and freshwater systems (see Section 4.1). We have subsequently funded research to include the capability to explicitly assess potential impacts of releases to estuarine, coastal and marine systems [62]. The objectives of the study are summarised below.

- representation of estuarine, coastal and marine systems facilitates explicit comparison with potential releases to terrestrial and freshwater systems. This allows the most conservative scenario to be robustly demonstrated
- capability to represent estuarine, coastal and marine systems broadens the range of biosphere systems that can be considered in assessments. This provides RWM with greater flexibility to assess potential environments that may be of particular interest to stakeholders, should such environments be identified as the site selection process moves forwards.

Consistent with the way in which potential releases to terrestrial and freshwater systems are assessed, the models for estuarine, coastal and marine systems are documented and justified in a way that is consistent with the IAEA BIOMASS approach [24].

The representation of estuarine, coastal and marine systems draws on an extensive study of hydrographic parameters for radiological assessments of coastal systems around England and Wales [92], see Figure 20.

Figure 20 Net exchange rate *versus* volume of coastal compartments [90]



Consideration of releases to estuarine, coastal and marine systems includes potential exposure of both occupational and recreational groups to maximise potential occupancies (in the occupational case) and to reflect behaviours that will be of general interest to stakeholders (in the recreational case).

Models for estuarine, coastal and marine systems are implemented in GoldSim, within the same case used for terrestrial and freshwater systems, facilitating the sharing of common data and allowing for integrated calculations to be considered. Further consideration will be given to the sensitivity of the new model to key processes and climate change[15].

[15] Task 002 of the Science and Technology Plan for Geological Disposal [10].

For modelling purposes, the coastal environment is taken to be bounded by the assumed cliff line or line of highest tide. On eroding coastlines, where the tidal limit is tending to move inland, this will generally coincide with either hard rock or soft rock cliffs, where soft rock cliffs include those composed of unconsolidated Quaternary sediments. At many locations, relict cliff lines will be present inland, reflecting earlier higher sea-level stands. The area between these former cliff lines and the present cliff line is considered to be part of the terrestrial environment.

In general terms, the coastal environment therefore comprises the beach (if present) and the foreshore down to the lowest low water mark. An important feature of this subsystem is that this region is inundated by the sea with a frequency ranging from every tidal cycle down to a few times per year. The coastal environment is also the component of the overall system that is most significantly influenced by wave action (though waves also influence the transport of bottom sediments in the near-shore coastal region where water depths are less than about 10 m). The storm beach is generally composed of coarse material, though some recent eroded finer material may also be present. The foreshore may be rocky, sandy or composed of abraded shells. In general, it contains little fine-grained material (clay and silt) as this is rapidly transported offshore. Where the foreshore is primarily sandy, it may also include gravel and cobbles. This coarser material may form a lag deposit which tends to protect the beach from erosion.

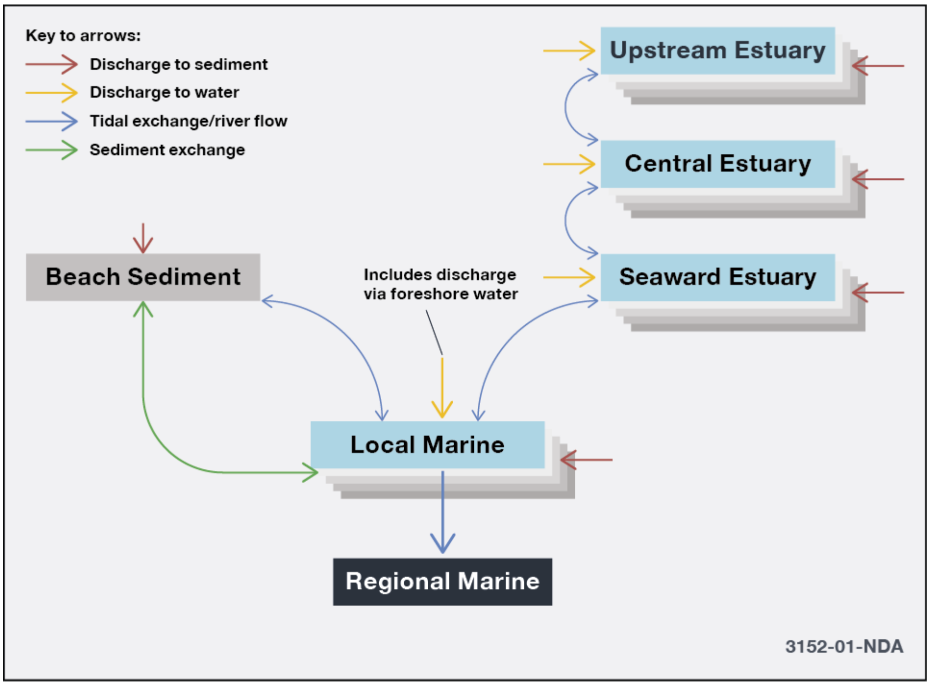
The marine environment reflects a region of coastal water within which contaminant concentrations can be considered to be homogenous following discharge in groundwater and/or from estuaries and/or the coast, based on consideration of the tidal ellipse and seafood collection and consumption habits. Consistent with models used to assess routine discharges to the marine environment (notably [92]), a reference coastline length of 10 km and a depth of 10 m are used, a reference off-shore distance of 2 km is used based on consideration of the resource use area of smaller fishing boats.

Because rivers can transport substantial quantities of sediment seaward, in some cases a delta may build up at the coast. In the UK, however, there are currently no rivers that have developed deltas that substantially modify the shape of the coastline. Sediments are generally deposited within estuaries or form submarine deltas offshore. Submarine deltas are appropriately considered as a component of near-shore and offshore marine sediments, so they do not need to be addressed as environmental components in their own right.

In addition, rivers, streams and terrestrial runoff may sometimes reach the coast via lagoons. Lagoons are distinguished from estuaries by having a continuous barrier between them and the sea. Thus, water exchange takes place through this barrier rather than as flow in open channels. Lagoons are rare around the UK and there is no significant driver for them to be explicitly represented in the model. However, as a first approximation, they can be treated as a limiting case of an estuary with a small tidal exchange rate. In the longer term, if a site were to be selected at which a lagoon was relevant, it might be appropriate to develop a site-specific model rather than treating the lagoon in this simplified manner.

The estuarine, coastal and marine systems are represented with compartments corresponding to the water column (and including suspended sediments) and compartments representing bed sediments. Processes that can move contaminants around the systems are represented as transfers between the compartments (for example, water flow and sedimentation/resuspension). Estuaries are sub-divided into up-stream, central and seaward sections, reflecting the different characteristics encountered. Bed sediments are represented with three compartments plus a ‘sink’, reflecting the potential for net sedimentation. Salt marshes are taken to be in equilibrium with the estuarine water which floods them on each tidal cycle. The overall compartment structure is illustrated in Figure 21, along with the main contaminant release and transfer processes.

Figure 21 Discretisation of the estuarine, coastal and marine components of the biosphere model [62]



Further details of the compartmental structure of the estuarine and marine component of the biosphere model, its mathematical form and its implementation in GoldSim are provided elsewhere [62]. Key physical data for parameterising the model are taken from UK-specific sources [92, 93], whereas radionuclide-specific data are largely taken from the database used to underpin the LLWR Environmental Safety Case [86]. Data for sorption are appropriate to marine and estuarine conditions and therefore implicitly include effects of isotopic dilution[16].

5.1.3 Biosphere dose conversion factors

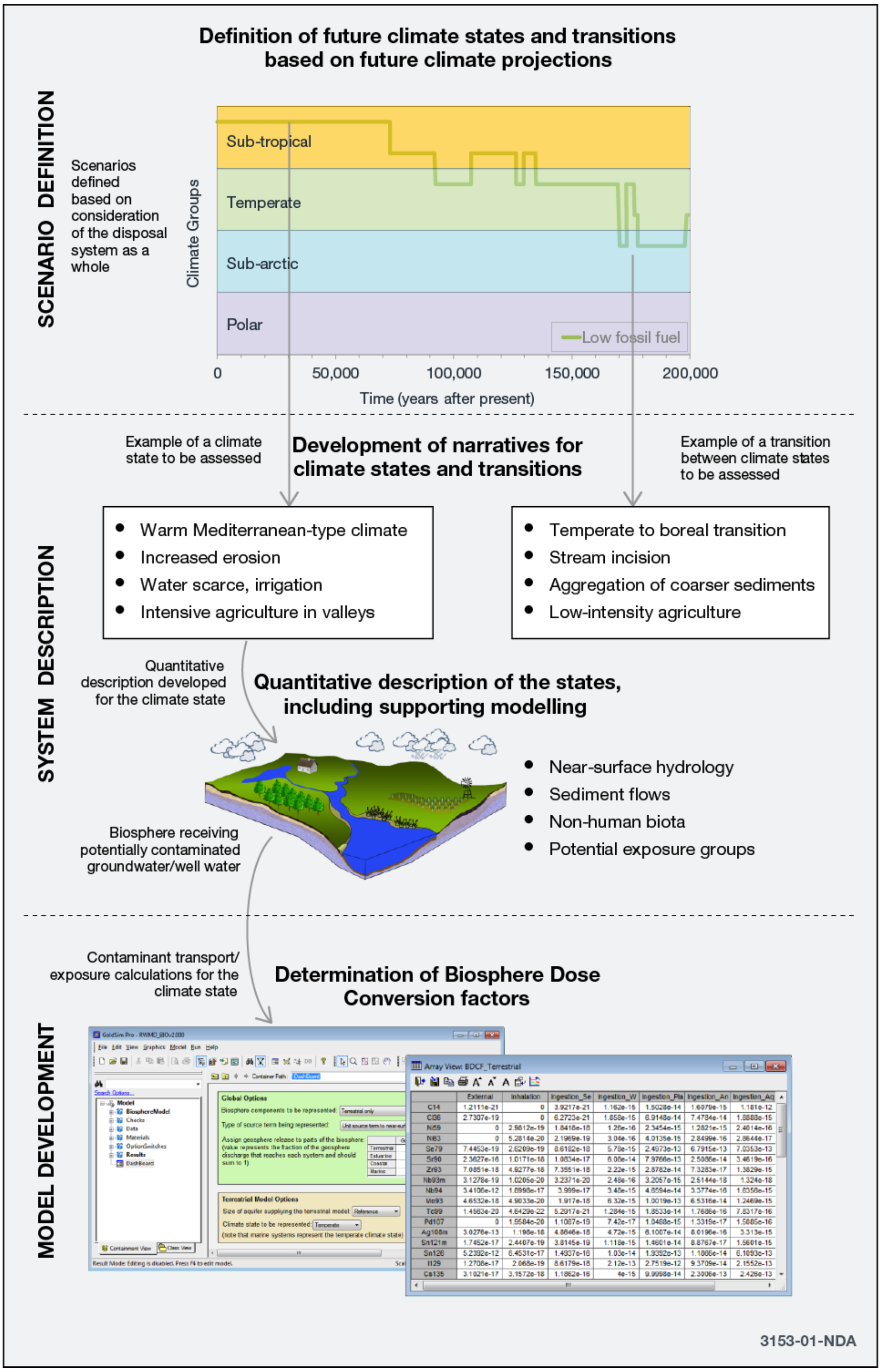
The long-term nature of radionuclide releases in groundwater allows equilibrium to be reached between releases to, and losses from, the biosphere system. This enables dose conversion factors to be calculated for continuous uniform releases to the biosphere.

The biosphere model is typically used to calculate annual effective dose rates at equilibrium for continuous uniform input rates of radionuclides. The use of biosphere dose conversion factors assumes equilibrium between radionuclide releases to and losses from the biosphere system being represented (however, the GoldSim models can also be used to simulate shorter-term, time-dependent releases, as required). The use of dose conversion factors is a conservative simplification for more highly sorbed radionuclides [Section 7.2.3 of 35] which might take thousands of years for doses to reach equilibrium

[16] Variation in salinity between brackish and marine water is about a factor of four, whereas the range in the sorption coefficient for chlorine in marine environments covers four orders of magnitude, thus isotopic dilution effects of ^{36}Cl are therefore not a dominant influence [62].

with releases to the biosphere. The way in which our biosphere approach delivers the biosphere dose conversion factors is illustrated in Figure 22.

Figure 22 Approach to developing biosphere models



In the case of the terrestrial and freshwater environment, the biosphere dose conversion factors are typically used for radionuclide discharges to the base of the subsoil and/or for constant concentrations in abstracted well water. The radionuclides entering the model may be the heads of multi-member radioactive decay chains. If this is the case, the model automatically calculates the in-growth and transport of radioactive daughters. Although any length of decay chain can be represented, a distinction is made between short-lived daughters that are treated to be in secular equilibrium at all times[17], and longer-lived daughters that are taken to exhibit their own kinetics of transport in the model domain.

For radionuclide releases to the terrestrial and freshwater environment under the five different climate states (temperate, warm humid, semi-arid, boreal and tundra), separate calculations can be made for well abstraction and natural groundwater discharge. However, for calculational purposes it is often convenient to aggregate these two sets of results and provide an overall combined dose factor for a flux of each radionuclide of 1 Bq y^{-1}. This is achieved through considering the flow rate in the near-surface aquifer and the area of groundwater discharge to the surface [9]. The resulting biosphere dose conversion factors are used in combination with calculated fluxes in groundwater from the geosphere to provide doses and associated risks for comparison against the risk guidance level. However, it is emphasised that the calculated results are not predictions of actual impact; rather they present a range of plausible indicators of possible impact and are used, together with other indicators of safety.

Biosphere dose conversion factors for releases to a temperate estuarine system are typically more than 1000 times lower than reference results for releases to temperate terrestrial and freshwater systems, where contamination is via both irrigation from a contaminated aquifer and discharge of contaminated groundwater to the soil [62]. Further sensitivity calculations are planned that will explore the robustness of the comparison and identify controlling characteristics and processes for the estuarine, coastal and marine systems[18].

Potential doses arising from direct releases of radionuclides in groundwater to the coast are comparable with, although on average lower than, those for a release to estuarine bed sediments. Similarly, potential doses arising from direct releases to the local marine system are also comparable with, although on average lower than, those for releases to the estuary. Results for some radionuclides (for example, ^{126}Sn) are higher for releases to coastal and marine systems, typically due to sorption onto marine bed sediments and external irradiation arising during occupancy of the beach.

Varying the size of the estuarine, coastal and local marine systems over plausible ranges results in a variation in dose factors of about 400 for estuarine systems, fifty for coastal systems and thirty for local marine systems. Reference results are towards the higher end of the range in all three cases. Thus, overall, the results confirm that the radiological impacts of releases of radionuclides to terrestrial and freshwater systems are typically substantially larger than the radiological impacts of corresponding releases to estuarine and marine systems.

The comparisons between the results for estuarine, coastal and local marine systems assume that all of the radionuclide discharges are directed to each system in turn and adopt generic assumptions with regards to the associated volume of discharging groundwater. These assumptions need to be reviewed when calculations are undertaken on a site-specific basis, albeit recognising the extremely long timescale under

[17] For the post-closure biosphere modelling, radionuclides with half-lives less than about 30 days are taken to be short-lived daughters. The list is given explicitly in [25].

[18] Task 002 of the Science and Technology Plan for Geological Disposal [10].

consideration. There is potential for uncertainty regarding contaminant releases to the biosphere to be reduced at the site-specific stage, through an evaluation of the potential for distribution of releases to different parts of the system, and refinement of discharge areas and volumetric groundwater flow rates.

5.1.4 Sensitivity of the biosphere dose conversion factors

The sensitivity of the biosphere model to different factors has been explored, including different geological contexts, uncertainty in parameters for important radionuclides and exposure of infants, children and embryos. The dose conversion factors are generally robust to within a factor of about ten against any of the individual factors considered.

A wide variety of calculations has been undertaken for terrestrial and freshwater environments with the biosphere model described in Section 5.1.1. These calculations have been undertaken with both the dynamic implementation of the model in GoldSim [25] and with a previous iteration of the model, which was implemented as a spreadsheet calculation and which solved the governing set of equations for equilibrium conditions only [94]. The results of the sensitivity studies remain within a factor of about ten of the reference case, with key sensitivities relating to the groundwater discharge area, the flow rate in the near-surface [27] and to parameters relating to key pathways for specific radionuclides (for example see [95, 96]). These results are summarised below:

- dose factors for warm humid and semi-arid climates are typically about a factor of 1.5 and 3.5 higher than those for a temperate climate, respectively, principally due to increased irrigation requirements and the importance of the well pathway for reference calculations. Results for a boreal climate are similar to those for a temperate climate, whereas those for a tundra system are only about one tenth of those for a temperate climate due to the reduced range of exposure pathways (e.g. an absence of irrigation) [25]
- use of the dynamic implementation to explore the timescales for the dose factors to approach equilibrium once contaminants reach the biosphere via the groundwater discharge pathway found that for the more mobile radionuclides[19], equilibrium is reached on a timescale of 100 years or less, whereas for the least mobile radionuclides[20], the timescale is about 10,000 years [35]
- the time dependence of the results for the well pathway is much less marked due to the inclusion of pathways relating more directly to the specified unit concentrations in the well water, notably drinking water ingestion and foliar interception of spray irrigation [35]
- a study of potential dose conversion factors for a range of different geological environments showed that the biosphere dose conversion factors may vary by up to a factor of ten, depending on whether the groundwater release and/or well pathway is considered, together with the associated discharge area and flow rates [27]
- radionuclide release to smaller marine systems result in higher dose conversion factors than for releases to larger systems due to the smaller volumes and the reduced degree of dilution [62]
- parameter sensitivity studies have been undertaken as reviews associated with the representation of key radionuclides; for example, a report on ^{36}Cl, ^{99}Tc and ^{129}I

[19] For example, ^{36}Cl, ^{99}Tc and ^{129}I.

[20] For example, ^{79}Se, ^{230}Th and its daughters (notably ^{226}Ra).

found that results remained within a factor of about ten of the reference case when alternative sets of parameter values were considered for key pathways [95]

- a comparison of committed effective doses to 10-year-old children and infants due to one year of exposure/intake with the reference results for adults found that results were within about a factor of two for most radionuclides, with factors of up to about four reported for some [97]
- consideration of exposures of the embryo, foetus and breastfed infant due to intakes by the mother showed that the committed effective dose might range up to a factor of about three times that of an adult over a one year period, but that the results obtained lay within the envelope of results obtained for 10-year-old children and infants [97]
- ratios of overall biosphere dose conversion factors for the cases with altered soil hydrology relative to the reference case were within a factor of two of the reference case [98].

The potential for bioturbation of soil and subsoil together with erosion and weathering of the bedrock to be effective in transferring relatively well sorbed radionuclides to the surface soil has been considered [35]. This study demonstrated that, for the groundwater discharge pathway, these processes have the potential to generate surface soil concentrations that are one or more orders of magnitude higher than generated by groundwater discharge alone for the most highly adsorbed contaminants once they have reached the near-surface.

5.2 Key radionuclides

Key radionuclides are identified and the set of such radionuclides is kept under review. Radionuclide-specific models have been developed for ^{14}C, which is important due to any potential gas pathway to the biosphere, and ^{36}Cl.

The biosphere models are supported in some instances by detailed studies and radionuclide-specific modelling, to build confidence in the stylised representation at the assessment-level. Key radionuclides are identified and kept under review, as described in Section 5.2.1.

Where necessary, consideration of key radionuclides extends to the development of contaminant-specific models. Such models have been developed for ^{14}C and ^{36}Cl, and are discussed in Sections 5.2.2 and 5.2.3 below. In future, additional such models may be developed, for example, for radionuclides such as ^{79}Se and ^{99}Tc that exhibit complex, redox-sensitive behaviour in soils [99].

We are directly funding research into the behaviour of key radionuclides in the biosphere. This research includes a component within the TREE programme concerning the biogeochemical behaviour of ^{129}I, ^{79}Se, ^{99}Tc and ^{235}U in soil-plant systems[21] [100] and the LO-RISE project, which is studying the behaviour of ^{14}C, uranium and radium radioisotopes in natural analogue environments in the UK[22] [101].

[21] Task 015 of the Science and Technology Plan for Geological Disposal [10].

[22] Tasks 786-790 of the Science and Technology Plan for Geological Disposal [10].

5.2.1 Identification and review of key radionuclides

Key radionuclides have been identified through a consideration of the inventory for disposal in the GDF, along with radioactive decay, in-growth and potential radiotoxicity.

There is uncertainty relating to the behaviour of long-lived isotopes in terrestrial and freshwater environments, particularly for radioisotopes and elements for which there is little or no empirical evidence from accidents or discharges to date[23]. Therefore, the models and data associated with key contaminants and exposure pathways are kept under review, both to take account of new information and to identify areas where further research would be beneficial. Having carried out a screening process to identify all radionuclides that should be included in a post-closure safety assessment [102], key radionuclides and associated exposure pathways relating to the ILW, HLW and SF inventories of UK wastes are also identified. These key radionuclides are listed in Box 5. The representation of some of these radionuclides in the biosphere has been reviewed in a series of detailed reports that identify potential topics that warrant further research. The first two of these reports covered ^{36}Cl, ^{79}Se, ^{99}Tc and ^{129}I [95, 96] and a further review has addressed the behaviour of radionuclides in the uranium decay chain [103, 104]. These reviews have led to innovative developments in process-based models to underpin assessments and these models have been documented in a series of journal papers [105, 106, 107, 108].

Box 5 Key radionuclides for intermediate level wastes, high level wastes and spent fuel (with half-lives in years)

^{14}C (5700)

^{36}Cl (3.01 10^5)

^{79}Se (2.95 10^5)

^{93}Zr (1.53 10^6) → **^{93m}Nb** (16.1)

^{94}Nb (2.03 10^4)

^{99}Tc (2.11 10^5)

^{126}Sn (2.3 10^5)

^{129}I (1.57 10^7)

^{135}Cs (2.3 10^6)

^{239}Pu (2.41 10^4) → **^{235}U** (7.04 10^8) → **^{231}Pa** (3.28 10^4) → **^{227}Ac** (21.8)

^{240}Pu (6560) → **^{236}U** (2.34 10^7) → **^{232}Th** (1.41 10^{10}) → **^{228}Ra** (5.75) → **^{228}Th** (1.91)

^{237}Np (2.14 10^6) → **^{233}U** (1.59 10^5) → **^{229}Th** (7340)

^{242}Pu (3.57 10^5) → **^{238}U** (4.47 10^9) → **^{234}U** (2.46 10^5) → **^{230}Th** (7.54 10^4) → **^{226}Ra** (1600) → **^{210}Pb** (22.2) → **^{210}Po** (0.379)

These are identified based on the inventory, radioactive decay, ingrowth and biosphere dose conversion factors. Some of these radionuclides are relatively short-lived and are included because there is a need to take into account their production in the geosphere and biosphere from longer-lived precursors. They are modelled explicitly because the timescales of some biosphere processes are sufficiently short that secular equilibrium with those longer-lived precursors cannot be assumed. Radionuclides with half-lives less than about 30 days are taken to be present in secular equilibrium with their parent, as noted in Section 5.1.3.

[23] For example, ^{36}Cl, ^{79}Se, ^{93}Zr and ^{94}Nb.

Participation in BIOPROTA enables RWM to discuss the representation of key contaminants in the biosphere and their associated data with other national radioactive waste management organisations that have a need to address many of the same issues. These interactions include comparisons of the structure of models used for assessment calculations, the data used in those models and the results obtained. These various studies enable the UK programme to remain up to date with parallel modelling and research that are being undertaken in other countries (see for example, [109]). To date, this participation has largely related to radionuclide behaviour in terrestrial and freshwater environments.

5.2.2 Carbon-14

^{14}C is an important potential contaminant in the context of geological disposal, both because of its potential to travel via a gas pathway, but also due to the importance of carbon to biological systems.

The behaviour of ^{14}C released in gaseous form to the terrestrial biosphere was investigated in detail by Nirex, taking account of the microbial metabolism of methane to carbon dioxide in the soil zone and the uptake by plants for use in photosynthesis of carbon dioxide released from the soil [110, 111, 112]. However, subsequently model inter-comparisons performed within BIOPROTA and reviews of the primary literature have identified that the assessment approach could be substantially improved, both by (i) updating the modelling, and (ii) undertaking field and laboratory studies to improve process understanding and to provide parameter values for the new generation of models. As a consequence, and within the context of our recent ^{14}C project, RWM has undertaken a series of three field and four laboratory experiments in which the transport of methane through soils, its oxidation in soils, and its uptake by plants have been investigated [113], see Box 6. The majority of these experiments have made use of carbon enriched in the stable isotope ^{13}C, but laboratory experiments with ^{14}C-bearing methane have provided data confirming the applicability of the ^{13}C data to modelling the behaviour of ^{14}C.

From a review of the literature [73], it was established that methane is consumed by oxidation in many soils, with oxidation rates typically being 0.25 mg m^{-2} d^{-1} in arable and agricultural systems, 0.58 mg m^{-2} d^{-1} in grasslands and 1.0 mg m^{-2} d^{-1} in forests. The methane oxidation rates observed in the laboratory and field studies are consistent with those found in the literature [73].

RWM has developed a process-based, mathematical model to interpret the experimental data [114]. The key processes represented are: diffusion of gases through partially saturated soil; microbial oxidation of methane; and soil respiration, which, together with diffusion, affects the background concentration profile of carbon dioxide in soil. The model also accounts for isotopic effects, but these are only a minor consideration. Application to the experimental data has delivered novel insights into the key process of methane oxidation. In particular, the experiments have been able to determine the rate at which microbes convert methane into an intermediate form (formaldehyde) and the fractions of the intermediate that are converted to biomass or carbon dioxide [114].

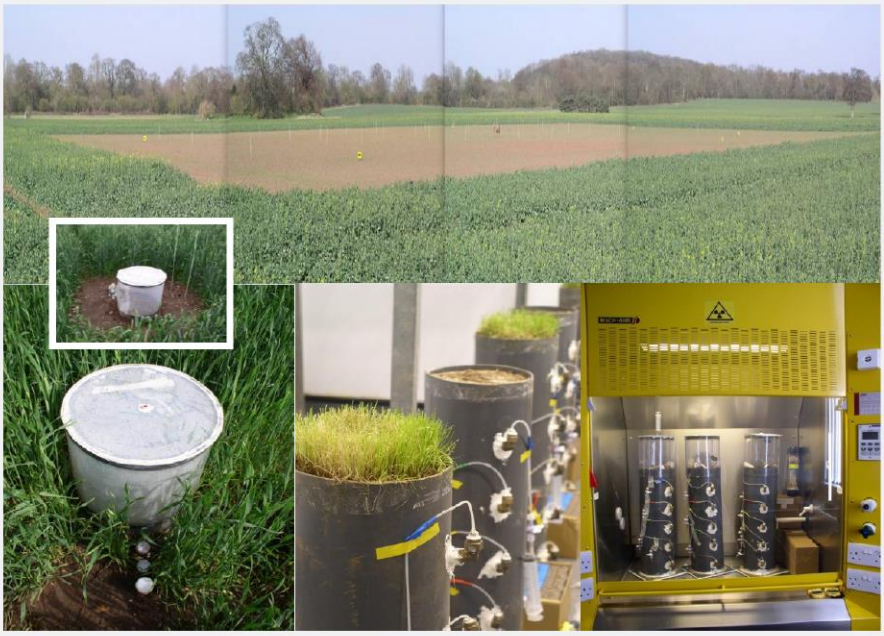
The process-based numerical model has been able to reproduce most of the gross features of the experiments and has demonstrated that the characteristic length scale over which methane is quantitatively oxidised to carbon dioxide in partially saturated soils is 0.04 to 0.35 m. This means that a large fraction of methane will be oxidised to carbon dioxide in a wide range of agricultural and grassland soils.

Box 6 Experimental studies relating to carbon-14 release to soils

Field experiments were undertaken at the University of Nottingham field station (see Figure 23) and these were complemented by a series of column experiments undertaken in the laboratory using soils from the site of the field experiment. In the field, methane enriched in ^{13}C was injected into the soil at a depth of 0.5 m. The bulk concentrations and isotopic compositions of methane and carbon dioxide were measured at various depths in the soil. As a result of a major enhancement in the sensitivity of the soil gas samplers used in these experimental studies, it was not necessary to constrain the lateral migration of the injected gas in the later experiments, as had been the case in the initial field trials. Development of the concentration and isotopic composition profiles of the gases with time allowed constraints to be placed on their diffusion coefficients in the soil and on the rate at which methane was metabolised to carbon dioxide. In addition, head chambers were placed on the soil surface at various times after injection of the isotopically modified methane, allowing gas fluxes across the soil surface (which could be either upward or downward) to be estimated. Both vegetated and unvegetated plots were studied.

Results from both the field and laboratory studies were interpreted using detailed models of diffusive transport and microbial metabolism, and results from these models were abstracted for use in the context of a simplified overall assessment model.

Figure 23 Field site, showing an experimental plot located within a larger cropped area



Notes: Lower left inserts show a head chamber in place. Bottles for collecting samples of soil gas are also visible in the lower of these two inserts. Lower centre and right inserts show vegetated and unvegetated soil columns being studied in laboratory conditions. Note the ports for soil gas sampling on the sides of the columns.

A new assessment model has also been developed, primarily for application to the gas pathway, although it is also readily adapted for use with releases of ^{14}C dissolved in groundwater [115]. The model builds on an earlier one developed by LLWR Ltd. [116]. It uses a simple, steady-state diffusion-reaction equation to describe the transport of methane, and its product carbon dioxide, through the soil. On this basis, it simulates the concentration of radioactive carbon dioxide in the soil; and the flux of radioactive carbon dioxide from the soil (likely to correspond to almost complete conversion of the methane).

The model then uses an atmospheric dispersion model to calculate the concentration of radioactive carbon dioxide in the atmosphere above the vegetation. Next, the concentration of radioactive carbon dioxide in the canopy of the vegetation is estimated using the concept of an aerodynamic resistance (the difference in the concentration of radioactive carbon dioxide between the plant canopy and the atmosphere is equal to the flux of the gas multiplied by the aerodynamic resistance). Finally the concentration of radioactive carbon dioxide in the canopy of the vegetation is used to determine the specific activity of the canopy atmosphere.

There are uncertainties concerning the concentrations of $^{14}CO_2$ in the canopy which arise from the necessary simplifications in the description of the canopy and from the atmospheric dispersion model used to describe processes above the canopy. The assumption is that the vegetation consists of small plants, with stable atmospheric conditions and a low wind speed. This is appropriate at the current stage of the programme, but probably constitutes a cautious set of assumptions [115].

As a result of photosynthesis, plants will fix carbon dioxide from the canopy atmosphere during daylight hours. Thus, neglecting isotopic discrimination, which is shown to be a small effect [115], the ratio of ^{14}C to stable carbon in the plant will be equal to that in the canopy atmosphere.

An additional uptake pathway allows for the possibility of carbon being taken up by the roots of plants by either active or passive processes.

As in previous models, the new assessment model assumes that grazing animals will derive most of their food from contaminated vegetation, but humans will derive only part of their diet (no more than 30%) from the local area (in particular, much of the dietary cereals and sugars would be sourced from elsewhere).

Note that the area over which a plume of contaminated gas is realised at the surface is assumed to be 10^4 m^2 (1 hectare); this is a cautious choice, since this is considered to be the smallest area that could provide a smallholder with a substantial fraction of their dietary carbon. For a smaller area, food from the contaminated area would need to be supplemented by food from elsewhere. If a larger area could be justified, then the doses would fall as the area increased [113].

Finally, a standard calculation is used to relate the specific activity of ^{14}C in humans to the effective dose rate.

5.2.3 Chlorine-36

The inventory, long half-life and mobility of ^{36}Cl mean that it is of interest in the context of geological disposal. A model for the behaviour of ^{36}Cl in the biosphere takes account of its high mobility, along with stable chlorine fluxes and the significance of organic compounds of chlorine.

Over the last twenty years, the potential importance of ^{36}Cl in determining the post-closure radiological impact of the GDF has been increasingly recognised. Furthermore, special considerations apply in respect of the behaviour of ^{36}Cl in soils and plants, notably its high mobility in chloride form, its strong association with organic matter in soil [117, 118] and the very high plant:soil concentration ratios that have been observed to occur [89, 119]. A model of ^{36}Cl behaviour in soils and plants has been developed in support of the assessment-level model [95, 120] and it has been applied in model inter-comparison studies undertaken within the BIOPROTA framework[24] (see [121]). The model includes stable chlorine fluxes, which are shown to be important in determining the behaviour of ^{36}Cl, and is used to justify the parameter values that are used in the assessment model. This modelling approach builds on over 20 years of experimental and modelling studies conducted at Imperial College [89], together with various studies on chloride and organic chlorine behaviour in field conditions. The model inter-comparisons undertaken in BIOPROTA provide further evidence of the robustness and applicability of the results obtained. The various modelling studies show that the behaviour of organic forms of chlorine in soil-plant systems are of limited relevance, provided that ^{36}Cl concentrations in soil are expressed relative to the chloride content and not the total elemental chlorine content. Plant uptake can then be characterised as arising from this chloride pool.

5.3 Impacts of non-radiological species on humans

In addition to radiological hazards, geological disposal facilities have the potential to release non-radiological species.

5.3.1 Comparison of adverse effects on health of ionising radiation and non-radiological species

The principal biological damage caused by ionising radiation occurs at the level of cell nuclei. Chemical toxins may also act as genotoxic agents, although their modes of action may be both more diverse and more contaminant-specific than those of ionising radiation.

Ionising radiation has an adverse effect on health, principally through its role as a genotoxic agent [122]. In conventional radiobiological theory, the initial events of significance are considered to be strand-breaks in DNA, some of which remain unrepaired and others of which are subject to misrepair. The consequences of such failures of repair include cell death and mutation. More recently, studies of genomic instability and the bystander effect[25] have raised the issue of alternative modes of action of ionising radiation. Thus, the target may be the whole of the cell nucleus rather than a localised region of DNA and the effect may be mediated by diffusible substances produced by the irradiated cell affecting others in its vicinity, or by other mechanisms involving the transmission of materials or signals across inter-cellular junctions. Nevertheless, the principal locus of action is considered to be the cell nucleus and the primary actions are considered to be cell killing (or sterilisation) and the induction of changes in the cell genotype and phenotype that lead to abnormal behaviour of the cell.

Chemical toxins may also act as genotoxic agents. However, their modes of action may be both more diverse and more specific than ionising radiation [122]. Although radioactive substances that are incorporated in the body may be associated with specific organs and

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[24] Task 046 of the Science and Technology Plan for Geological Disposal.

[25] The bystander effect is the phenomenon in which unirradiated cells exhibit irradiated effects as a result of signals received from nearby irradiated cells.

tissues, for example, ^{131}I with the thyroid and ^{239}Pu with bone surfaces, the emitted radiation causes non-specific damage. In contrast, chemicals can induce their effects by binding to specific ligands and altering particular biochemical pathways. These ligands and pathways differ between chemicals. Thus, whereas each individual chemical will have a specific mode of operation, the wide range of chemicals to which humans are exposed makes their range of adverse effects more diverse than is observed with ionizing radiations. However, this does not rule out similar modes of action in some cases. Thus, for example, both cadmium and nickel can induce genomic instability, a phenomenon first identified in the context of exposure to ionising radiation [123].

5.3.2 Health risks from non-radiological species

Beryllium, cadmium, chromium, lead and uranium have been identified as being of relevance. However, studies have suggested that non-radiological species will not have a significant adverse effect on safety.

The impacts of non-radiological species that could potentially be released from the GDF have been examined in various screening studies (for example [124]). Whilst there is an internationally agreed regulatory regime for radionuclides, based upon ICRP recommendations, that prescribes the calculation of effective dose and its relation to health risks, no such agreed procedure exists for non-radiological species individually, in combination with each other, or in combination with radiation exposure. In the absence of such an agreed position, the approach to assessing non-radiological species has to go further than that for ionising radiation by discussing the relationship between exposures and risks to health.

A detailed study has been undertaken that considered the most relevant substances in the UK radioactive waste inventory and the health risks associated by exposure to these substances[26] [125] (see Box 7). This included an examination of the potential for combined effects between the various substances and also with exposure to ionising radiations [122]. Potential for synergistic effects between radiological and chemical contaminants will also be revisited as part of our forward research programme[27].

The following substances were identified as being of particular relevance for study: beryllium, cadmium, chromium, lead and uranium[28], on the basis of their presence in the UK radioactive waste inventory, toxicological properties and the previous work [125]. These substances have also been considered in other studies [126, 127]. Overall, the detailed study [125] found that for the most realistic, but still cautious, case examined all the projected impacts were low, both for the various substances considered individually and for all of them considered in combination and in the presence of simultaneous exposure to ionising radiation.

[26] Tasks 051, 052, 053 of the Science and Technology Plan [10].

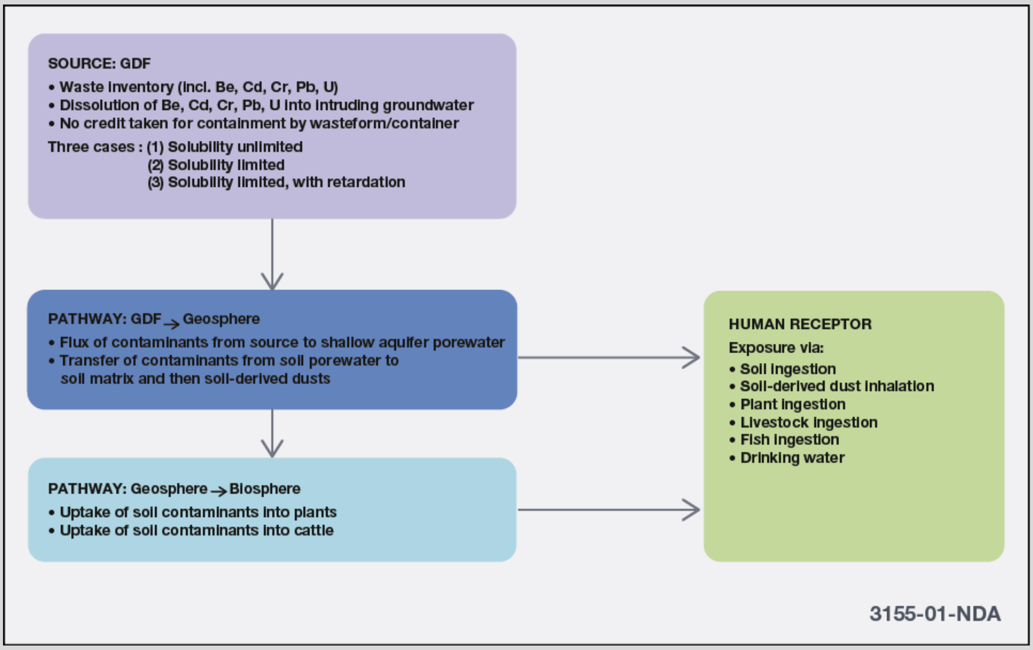
[27] Task 054 of the Science and Technology Plan [10].

[28] Note that organic contaminants are screened out on the basis of their chemical and microbial degradation associated with the likely travel times via the groundwater pathway.

Box 7 Study of health risks associated with non-radiological species

For beryllium, cadmium, chromium, lead and uranium, human health risk assessments were undertaken for three different cases, with each successive case including a lower degree of conservatism (see Figure 24).

Figure 24 Methodology and cases considered (adapted from [128])



In all three cases considered, beryllium was always considered to have unlimited solubility. Cases 2 and 3 were subdivided into two variants, depending on whether or not solubility enhancement due to cellulose degradation products was taken into account. Two different environmental settings were considered for each case: basement rock to surface; and basement overlain with permeable sedimentary rock.

In addressing possible combined effects between the various substances and also with exposure to ionising radiations, three topics were identified from the very cautious Case 1 that warranted consideration:

- combined effects on the kidneys from ingestion of cadmium, uranium and lead
- combined effects between ingested lead and exposure to ionising radiation with respect to induction of various types of cancer
- combined effects between all five key substances and exposure to ionising radiation with respect to lung cancer induction.

For the more ‘realistic’, but still cautious, Case 3 (solubility limited, with retardation), it was found that none of the calculated total daily oral or inhalation intakes exceeded toxicological assessment criteria. In these circumstances, where the adverse health impacts of the individual substances are likely to be non-existent, or very small, synergistic effects can reasonably be neglected.

The general approach adopted in this work will be used to inform future safety cases. The work undertaken so far has allowed RWM to define a limited number of substances that are worthy of detailed consideration and provides a basis for enhancing the realism of the scenarios studied. Specifically, uranium is identified as being of both radiotoxic and chemotoxic significance. For this reason, we have undertaken a detailed review of the relative importance of its radiotoxic and chemotoxic properties, giving consideration to both the ingestion and inhalation of different physical and chemical forms of the element, the degree of enrichment or depletion, and the extent of ingrowth of radioactive daughters. This study has shown that either radiotoxicity or chemotoxicity may be the dominant consideration, depending on details of the exposure regime [129].

In parallel, we are giving consideration to demonstrating that the GDF will comply with groundwater protection requirements for both radionuclides and non-radiological species. The Disposal System Technical Specification (DSTS) explicitly recognises the need to comply with the Groundwater Daughter Directive, as implemented in the Environmental Permitting Regulations 2010 (EPR10). EPR10 contains specific requirements to address the impact of hazardous substances and non-hazardous pollutants:

> "*In accordance with the groundwater protection provisions of the Environmental Permitting (England and Wales) Regulations 2010, it shall be demonstrated that all necessary technical precautions will be observed to:*
>
> - *prevent the input of hazardous substances to groundwater; and*
> - *limit the input of non-hazardous pollutants to groundwater so as to ensure that such inputs do not cause pollution of groundwater.*"

The manner by which these requirements are addressed for a specific site will need to take account of our understanding of the characteristics of the site and in particular, the delineation and characteristics of groundwaters at depth and in overlying groundwater bodies.

At this generic stage, our approach to assessments will be in accordance with the objectives of the Directive, with respect to the requirements to limit and prevent.

Changes introduced by new package types also have important implications in this research area, in particular insofar as they may affect the quantities of non-radiological species likely to be present in the GDF. For example, some proposed new waste package types may potentially have an optional lead shielding component. This may cause a significant increase in the mass of lead in the inventory, which, when coupled with the chemotoxicity of lead, introduces the potential for groundwater contamination which requires consideration.

Previous studies have assumed that radionuclides and the stable species considered are released instantly into backfill porewater at the time of GDF closure. However, for stable species such as lead, the assumption of instant release will be overly cautious, especially when used as a bulk shielding material, since the corrosion of lead in high-pH, reducing environments, such as that in a cementitious GDF, is likely to be low. To accommodate this, future assessment models may incorporate a uniform release of lead into solution, over a specified timescale. This timescale depends on the corrosion rate of lead and the thickness of the lead sheet or shielding that is undergoing corrosion. A study has recently been undertaken by LLWR Ltd. to elicit corrosion rates for lead, under the expected chemical conditions in the trenches and vaults [130].

Recently, RWM has undertaken both general screening and assessment studies on non-radiological substances, and studies of specific substances, including lead and mercury. RWM has also carried out a qualitative and quantitative study on the potential post-closure behaviour of a wide range of hazardous substances in the GDF. These studies are discussed further in [4].

Overall, it is considered that future assessments of releases of non-radiological species from the GDF will need to include some degree of consideration of potential combined effects for both chemical mixtures and for cases where there may be significant exposures to both chemical and radiological hazards. However, the studies undertaken to date suggest that potential releases of non-radiological species from the GDF based on the 2013 Derived Inventory [131] and accepted waste package types, will not have a significant adverse effect on safety.

5.4 Radiological impacts on wildlife

Requirements for wildlife dose calculations are yet to be fully established at an international and national level. The biosphere models for human dose assessment provide radionuclide concentrations in a range of environmental media. These can be used, together with internationally accepted tools, to assess the impact of radiation on wildlife.

The regulatory framework within which assessments relating to wildlife are undertaken reflects the status of the developing international recommendations in this area (for example [19]) and is not, as yet, well defined. However, the EU funded ERICA project produced an assessment tool that can be used, together with estimated biosphere concentrations generated from the models summarised in Sections 5.1.1 and 5.1.2, to calculate dose rates to reference organisms that could be evaluated relative to an appropriate dose-rate screening criterion [132].

The selection of appropriate screening criteria has been addressed within the EU-funded PROTECT project [133]. In addition, relevant data for use in assessment studies have being compiled through IAEA co-ordinated programmes, which have provided input to recommended parameter values for use in models [134]. We continue to support on-going collaborative studies aimed at developing understanding and assessment of potential impacts on wildlife, notably through our support of the TREE project [100] along with several associated working groups within the IAEA's MODARIA programme[29] [40].

TREE is one of three projects within the Radioactivity and the Environment (RATE) programme funded by the National Environment Research Council, the Environment Agency and RWM. The overall objective of the TREE project is to reduce uncertainties in estimating the risks, to humans and wildlife, associated with exposure to radioactivity, and to reduce unnecessary conservatism in risk calculations. This is being achieved through four interlinked science components beginning with improving our understanding of the biogeochemical behaviour of radionuclides in soils through to studying the transgenerational effects of ionising radiation exposure on wildlife[30]. TREE has close interactions with EU-sponsored programmes such as COMET, the STrategy for Allied Radioecology (STAR) Network of Excellence and the European Radioecology ALLIANCE, which are directed primarily at advancing both fundamental and applied aspects of radioecology (see [135] and links to other programmes provided therein).

Notwithstanding the developments in approaches and recommendations in relation to wildlife, and consistent with the approach adopted within the OESA [12,136], a preliminary assessment of potential impacts from the GDF has been undertaken using the ERICA Tool [137]. The results are significantly lower than all of the benchmarks and screening values currently in use, which implies that there is likely to be a low risk to wildlife associated with releases of radionuclides from the GDF.

[29] Tasks 011, 012, 013 of the Science and Technology Plan for Geological Disposal [10].

[30] Tasks 014-018 of the Science and Technology Plan for Geological Disposal [10].

6 Concluding remarks

The science and technology underpinning geological disposal of the materials currently considered in the UK radioactive waste inventory is well established. The knowledge base includes information from laboratory studies, demonstration experiments, models and studies from archaeological and natural analogues that can be used to support the implementation of geological disposal.

The key message emerging from the analysis presented in this status report is that the current biosphere methodology and models are fully consistent with international recommendations and the present context, and are underpinned by appropriate research. Specifically:

- the biosphere is where key end points relating to the effectiveness of the disposal system are determined, including potential environmental concentrations and potential exposures of humans and of other organisms
- the methodology covers potential releases of radionuclides and non-radiological species from the GDF that may reach the biosphere by transport in groundwater. Issues relating to gas generation, migration and behaviour in the biosphere are also covered
- this status report gives an outline of the key processes and understanding underpinning the representation of the biosphere and how the biosphere may evolve over the long time-scales of relevance to post-closure safety including a reviewed approach to climate change
- consideration of processes associated with the long-term evolution of the biosphere is important in defining the boundary conditions for the geosphere and identifying potential sources of disturbance to the safety functions performed by different barriers within the disposal system; the biosphere does not constitute a barrier in itself
- RWM's biosphere modelling capability has recently been extended from a solely terrestrial model to allow potential contaminant releases to estuarine, coastal and marine systems around the UK to be represented
- significant effort has been made to justify and ensure consistency in the radionuclide-dependent data used. The database used with the model will continue to be updated in light of key new sources of information. In addition, RWM has radionuclide-specific models tailored to the particular environmental characteristics of key radionuclides, supporting their representation at the assessment-level.

Information contained in the suite of research status reports has been used to underpin the development of the 2016 generic DSSC. In particular, information from this status report has been used to provide the technical understanding of the processes associated with the long-term development of the biosphere.

RWM recognises areas that require further development and issues that can only be resolved as the GDF site selection process progresses towards site-specific assessments.

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