BIOPROTA

Key Issues in Biosphere Aspects of Assessment of the Long-term Impact of Contaminant Releases Associated with Radioactive Waste Management

An Exploration of Approaches to Representing the Geosphere-Biosphere Interface in Assessment Models

FINAL REPORT ON THE PROJECT

Version 2.0, Final
11 December 2014

PREFACE

BIOPROTA is an international collaboration forum that seeks to address key uncertainties in the assessment of radiation doses in the long term arising from release of radionuclides as a result of radioactive waste management practices. It is understood that there are radio-ecological and other data and information issues that are common to specific assessments required in many countries. The mutual support within a commonly focused project is intended to make more efficient use of skills and resources, and to provide a transparent and traceable basis for the choices of parameter values, as well as for the wider interpretation of information used in assessments. A list of sponsors of BIOPROTA and other information is available at www.bioprota.org.

The general objectives of BIOPROTA are to make available the best sources of information to justify modelling assumptions made within radiological assessments of radioactive waste management. Particular emphasis is to be placed on key data required for the assessment of long-lived radionuclide migration and accumulation in the biosphere, and the associated radiological impact, following discharge to the environment or release from solid waste disposal facilities. The programme of activities is driven by assessment needs identified from previous and on-going assessment projects. Where common needs are identified within different assessment projects in different countries, a common effort can be applied to finding solutions.

In post-closure radiological safety assessments of geological disposal facilities/geological repositories for radioactive wastes, models are developed and applied for transport of radionuclides through the engineered barriers and surrounding host rock towards the biosphere. As radionuclides migrate through the host rock they approach and enter more superficial strata. Although the safety of geological disposal facilities is generally considered to rely primarily on isolation of the wastes from the accessible environment, in determining the radiological impacts of any releases of radionuclides in relation to the regulatory criteria typically employed there is a need to evaluate the degree of dilution and dispersion in the superficial strata, together with any re-concentration that may occur (e.g. as a result of bioaccumulation). To some extent, the degree of dilution and dispersion that occurs in the superficial strata may be explored in the geosphere models deployed in the safety assessment, e.g. by 2D or 3D modelling of the radionuclide plume. However, even if this is done, there is likely to be a need to explore in more detail what happens in the top few tens of metres where upwelling groundwaters interact with surface water bodies and/or infiltrating meteoric water. Models for the superficial zone (here generally described as the geosphere-biosphere interface, GBI or geosphere-biosphere subsystem, GBS) are, overall, not as well developed as those for various host rock types or for reference biospheres. A project was therefore undertaken to look at the features, events and processes that may need to be included in conceptual models of the GBI, to evaluate existing understanding of those processes and to consider how mathematical models could be developed on the basis of such understanding.

The starting point for this project was the development of an initial briefing note that explored the types of GBI that have been considered within long-term safety assessments. This briefing note provided a significant input to a workshop that was hosted by NDA/RWMD in London, UK. Here the different GBI's were presented and discussed, alongside other relevant inputs provided by workshop participants. A report of this workshop was then prepared.

A second briefing note was prepared as input to the second and final workshop on this project, hosted by Andra at Châtenay Malabry, Paris, France, in March 2014. In this second briefing note, a methodology was developed for characterising the geosphere-biosphere interface in a wide range of assessment contexts. Three illustrative climate and landscape evolution scenarios were then described and the methodology developed for characterising the geosphere-biosphere interface was applied to two of these three scenarios in order to define a set of geosphere-biosphere interface sub-systems for which conceptual models need to be developed. This then led into application of the second part of the methodology for creation of these conceptual models.

The second workshop reviewed this briefing note, ongoing work in the related International Atomic Energy Agency's MODARIA Project (specifically the work on MODARIA Working Group 6 on climate change and landscape development), and various model development, model application and assessment-related activities being undertaken by the participant organisations. A report of this second workshop was then prepared.

In addition to the two briefing notes and workshop reports, a detailed paper on the project was prepared and published in the Journal of Environmental Radioactivity.

This final report on the project brings together key information from the two briefing notes, workshop reports and published paper. In addition, it includes new material developed on the basis of those documents and provides an evaluation of the current position in respect of issues relating to the GBI, as well as a discussion as to how work in this area could be developed in the future. The report was prepared by the project Technical Support Team, M C Thorne, S F Mobbs, K Smith, R George and G Smith, based on a large number of substantial contributions from workshop and other project participants. Financial support for the project was provided by the Agence Nationale pour la Gestion des Déchets Radioactifs, Electricité de France, the Korea Atomic Energy Research Institute, the Norwegian Radiation Protection Authority, the Nuclear Waste Management Organization of Japan, the Nuclear Waste Management Organization (Canada), the Radioactive Waste Management Directorate (UK), the Svensk Kärnbränslehantering AB (Sweden) and the Swedish Radiation Safety Authority.

The report is presented as working material for information. The content may not be taken to represent the official position of the organisations involved. All material is made available entirely at the user's risk.

Version History

Version 2.0: Final report prepared by the project Technical Support Team, taking into account comments from project participants on the version 1.0 report.

Version 1.0: Draft final report prepared by the project Technical Support Team based on contributions from project participants.

CONTENTS

1. INTRODUCTION

In post-closure radiological safety assessments of geological disposal facilities/geological repositories for radioactive wastes, models are developed and applied for transport of radionuclides through the engineered barriers and surrounding host rock towards the biosphere. Attention in such modelling is generally focused on radionuclides dissolved in groundwater, but transport in the gas phase has also been considered in some relevant cases, as well as the release of radionuclides bound to material being eroded at the surface.

As radionuclides migrate through the host rock they approach and enter more superficial strata. Whereas the role of the engineered barriers and host rock is generally to prevent or retard the migration of radionuclides, in the more superficial strata retardation may be of less importance compared with dilution and dispersion (though retardation in these superficial materials may nevertheless be a relevant factor to take into account, and reconcentration, e.g. due to biotic processes, may also need to be addressed). Although the safety of geological disposal facilities is generally considered to rely primarily on isolation of the wastes from the accessible environment, in determining the radiological impacts of any releases of radionuclides in relation to the regulatory criteria typically employed there is a need to evaluate the degree of dilution and dispersion in the superficial strata, together with any re-concentration that may occur (e.g. as a result of bioaccumulation).

To some extent, the degree of dilution and dispersion that occurs in the superficial strata may be explored in the geosphere models deployed in the safety assessment, e.g. by 2D or 3D modelling of the radionuclide plume. However, even if this is done, there is likely to be a need to explore in more detail what happens in the top few tens of metres where upwelling groundwaters interact with surface water bodies and/or infiltrating meteoric water. Models for the superficial zone (here generally described as the geosphere-biosphere interface or GBI) are, overall, not as well developed as those for various host rock types or for reference biospheres. In the deep geological zone, there is generally a requirement to evaluate radionuclide isolation and transport based on the present structure (possibly with limited alterations, e.g. due to seismic effects), though with changing boundary conditions reflecting large-scale changes in climate and landform. Thus, the model is taken to be predictive of the future conditions of relevance at the site of interest. In contrast, the biosphere systems selected for use in the safety assessment are generally taken to be representative of the range of situations that could occur, but there is no implication that they are predictive of the situations that will occur [BIOMASS, 2003].

In the superficial zone, the stability of the system is likely to be such that its particular characteristics should be taken into account in the safety assessment. Nevertheless, it will alter with time and consideration has to be given to the degree to which that evolution should be modelled explicitly and the timescale over which there should be a transition to more schematic modelling. Furthermore, the spatial scale of modelling has to be considered, as fine details of the projected distribution of radionuclides may not be needed for an overall evaluation of radiological impacts.

As concluded in the BIOPROTA project on the U-238 decay chain [Limer et al., 2012] there is a need to explore what features, events and processes (FEPs) ought to be included in conceptual models of the GBI and to evaluate existing understanding of those processes (including the availability of mathematical models of some of those processes and their interactions). From this exploration, it should be possible to synthesise an account of what needs to be included in a model or models of the GBI, and how such a model or models could be developed on the basis of existing understanding. This has been the principal focus of the BIOPROTA GBI project. Specifically, the project aimed to explore what features, events and processes (FEPs) should be included in conceptual models of the GBI and to evaluate existing understanding of those processes (including the availability of mathematical models of some of those processes and their interactions) and, from this exploration, to synthesise an account of what needs to be included in a model or models of the GBI, and how such a model or models could be developed on the basis of existing understanding. Such development may involve fundamental research activities, and not merely be the combination of existing mathematical or simulation models into an overall system model.

1.1 WHAT IS MEANT BY THE GEOSPHERE-BIOSPHERE INTERFACE?

Throughout the period of the project, there was considerable discussion amongst the participants about how the GBI should be defined, or even whether it was a useful concept for system description, conceptual modelling or mathematical modelling. Clearly, in the real world there is no entity that would be generally described as the GBI. Furthermore, in developing a descriptive model of a specific site there may be no need to include a distinct component of the description relating to the GBI. Rather, discipline-specific descriptions, e.g. of the solid geology, hydrogeology, hydrogeochemistry, overburden characteristics and ecosystems, may be appropriate, with each description applicable to a spatial domain appropriate to that discipline. This suggests that the role of a GBI may first emerge when the overall disposal system is being conceptualised for assessment-modelling purposes. Even at this stage, it may not be necessary to specifically develop a conceptual model of the GBI. For example, the hydrogeological and hydrogeochemical model may extend from below repository depth to the ground surface and may interface directly with a biosphere model based on the biogeochemical cycling of elements in ecosystem components. However, this example illustrates the potential utility of a conceptual and mathematical model of the GBI. Such a model might represent the region between the upper part of the host rock and the overlying soil-plant system, such that it addresses the transition zone between the domain in which contaminant transport is dominated by hydrogeological and geochemical considerations and the domain in which contaminant transport is dominated by surface hydrological and biotic processes.

It was further recognised that although the GBI may be found useful in conceptual modelling, this utility may not carry over into mathematical modelling, where various tools may be employed to evaluate the significance of various subsets of processes identified as being of potential significance. The conceptual model of the GBI may be used either to inform development of such mathematical modelling tools, or to audit the existing set of available tools to determine whether they adequately represent the key components of the GBI and the interactions between them that are identified in the conceptual model.

It follows from the above that the GBI adopted will depend on both the specific or generic site to be assessed and the requirements that are placed upon the assessment. That is to say, it will depend upon the assessment context, in the sense that this is defined in BIOMASS [2003]. Although the GBI can, in principle, be defined both for deep and shallow disposals of solid radioactive wastes, in practice, in the case of shallow disposal, the repository is likely to be embedded in a zone that is relatively stable, but that is susceptible to significant change over the assessment period. Thus, in respect of the broad definition of the GBI used in this report, the repository may be considered to be embedded in the GBI rather than being located in the geosphere below it. This may apply particularly where the repository is excavated from the surface, since all the overlying materials will necessarily have been engineered to some degree, so the engineered facility could be considered to extend from depth to the surface.

In view of the above, with a near-surface disposal facility, it may be best to develop a conceptual model of the disposal system as a whole. It is suggested that the methodology set out in this report for developing conceptual models of the GBI may also be useful in this context. The principal implication is that the interaction matrices used for developing such conceptual models would need to be expanded to include the main engineered components of the repository on the lead diagonal. In the case of a deep repository, it is likely to be possible to treat the engineered components and their interactions with the host rock as a distinct subsystem with its own conceptual model.

In the foregoing, the emphasis is placed on developing conceptual and mathematical models to represent the GBI. However, workshop participants emphasised that all such model development must be underpinned by good scientific understanding, particularly of the processes that occur and of how they should be represented in a modelling context.

1.2 THE APPLICATION OF A TYPOGRAPHY OF REPOSITORY TYPES

Because the GBI or GBIs adopted will be system specific, it is useful to consider the extent to which GBI characteristics might differ between various contexts. Such a consideration is likely to be facilitated by use of the typography of different types of disposal system that is being developed by MODARIA Working Group (WG) 6. This typography is illustrated in Figure 1.1.

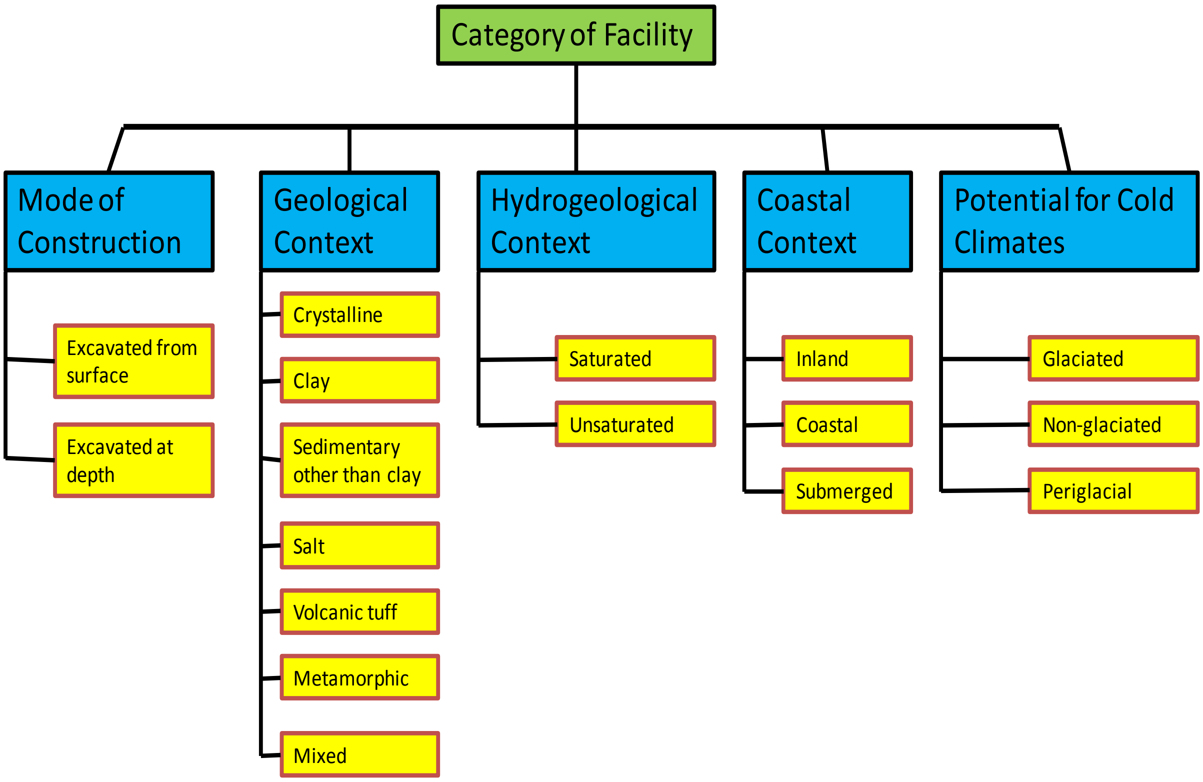

Figure 1.1: Typography of Types of Disposal Facility, as being developed by MODARIA Working Group 6 (from the presentation to the Final Plenary Session at the November, 2013 Annual MODARIA Meeting, IAEA, Vienna, Austria)

Some comments are required in respect of Figure 1.1. These are given below on a category by category basis.

Mode of Construction: The distinction is between facilities that are constructed in bulk excavations from the surface from those that are accessed by shafts or adits, with the excavation of the storage volumes occurring at depth. It is emphasised that facilities constructed in bulk excavations from the surface range from simple unlined pits and trenches through to highly engineered structures. It should be noted that facilities excavated from the surface can have the wastes disposed entirely below grade, or they can have a waste stack that has its base below grade, but is sufficiently high that the top of the stack is above grade. Disposal entirely above grade is also possible. Whether disposal is entirely or partly below grade, the waste stack may be covered by some form of cap that would typically form a dome or more complex mound structure rising above the general level of the ground.

Geological Context: The primary consideration is the host geology. In some contexts, the same category of rock extends from repository depth to the surface, but there are other contexts in which a sequence of different types of formation is present. Such a sequence is described as mixed. In general, salt (either bedded or as a dome or pillow) would be present in a mixed sequence, as it would be overlain by a cap rock preventing dissolution of the salt. However, as this is necessarily the case, where the host rock is salt this determines the categorisation. Sedimentary formations include both consolidated and unconsolidated materials such as Quaternary sediments. Clays are distinguished by their plasticity from harder rocks derived by consolidation of the same material, e.g. shales. Mudstones fall close to the boundary and might be classified either with clays or with other sedimentary rocks, depending on their local characteristics. Facilities that are excavated from the surface will typically be located in unconsolidated sediments, but this is not necessarily the case.

Hydrogeological Context: Here the distinction is between whether the repository is located above or below the regional water table. If it is located below the regional water table, it will eventually become saturated, though it may remain unsaturated for a considerable time after repository closure depending on the hydraulic conductivity of the host rock. A repository located above the regional water table will generally be unsaturated, though saturated regions may occur, e.g. due to perched water present in the local geological strata or ponding of water in the engineered structures.

Coastal Context: The current global sea-level is within a few metres of the highest sea-levels that have been experienced during the Quaternary and future sea-level increases due to melting of ice-sheets and thermal expansion of the oceans are likely to be less than 20 m (see Appendix A of Fish *et al.*, 2010). Thus, sites that are currently well above sea level are likely to remain so for the whole period for which quantitative assessment studies are required. In contrast, during glacial episodes, global sea-levels have fallen to as much as about 120 m below their current position. A fall of this magnitude would result in much of the continental shelf becoming exposed. Thus, sites that are submerged at the present day may become coastally located in the future. However, these sites are classified as submerged for the purpose of this scheme. They would typically be located offshore, but accessed from land. Coastal facilities are located onshore, but at an elevation of less than about 20 m. They may be subject to processes such as coastal erosion and inundation, particularly under conditions of rising sea-level due to anthropogenic greenhouse-gas induced global warming. However, they may also become protected from these processes if global sea levels fall or if there is local isostatic uplift of the land. It is emphasised that the interplay of eustatic and isostatic changes in sea-level is strongly dependent on the site under consideration. For example, eustatic sea-level changes will differ substantially on a regional basis due to alterations in the geoid arising from changes in the distribution of the Earth's mass, e.g. from the loss or significant diminution of the Greenland ice sheet, and isostatic changes will be strongly dependent on the history of ice loading and unloading local to the site.

Potential for Cold Climate: Here, the distinction is between areas that have been subject to glaciation in the past, those that were never glaciated and those that were never glaciated, but experienced sub-zero ground temperatures giving rise to periglacial processes. In this context, 'glaciation' is defined to mean the occurrence of ice cover at the location of the facility. This distinction is made because glacial, periglacial and non-glacial processes have very different effects on the disposal system (comprising the engineered facility, host geological environment and overlying biosphere). Glacial processes include those originating from isostatic adjustment under the weight of the ice, erosion and deposition due to the advancing and retreating ice sheet, and those processes associated with the very active hydrological regime that exists below and at the margin of an ice sheet. In particular, the groundwater flow regime may have profound effects on groundwater chemistry down to depths of hundreds of metres, with implications both for the integrity of the engineered barriers of a facility and for the rate and pattern of radionuclide transport arising if those barriers are breached. Periglacial processes include enhanced solifluction, the formation and decay of ground ice, and gross changes in the hydrological characteristics of the regolith and underlying solid rock due to ground freezing. In non-glaciated regimes, fluvial and Aeolian processes play a predominant role in reshaping the landscape. In principle, the non-glaciated regions could be further distinguished, e.g. into temperate, sub-tropical and semi-arid and arid regimes. However, the processes of relevance in these regimes are similar, though their rates may vary substantially, whereas both periglacial and glacial regimes are associated with suites of processes that do not apply in warmer climatic conditions. Furthermore, it is a consideration that many of the repositories that are currently being planned are located in areas subject to glaciation or frozen-ground effects at some stage of the global glacial-interglacial cycle.

1.3 STRUCTURE OF THE REPORT

The project began with a consideration of the way in which the GBI has been represented in previous assessments. This information was compiled in the first briefing note for the project [BIOPROTA, 2013a] and an edited version of this material is provided in Appendix A. This takes into account discussions at the first Workshop [BIOPROTA, 2013b]. A brief summary of the then current position (March 2013) is presented in Section 2, together with an account of the various types of GBI that are likely to be of relevance. Following the first Workshop, a methodology for defining conceptual models of the GBI was developed and applied to various example situations. This work was described in the second briefing note on the project [Thorne, 2014] and in a journal paper [Smith et al., 2013]. An edited version of the material in the second briefing note is provided as Appendix B. This takes into account discussions at the second Workshop [BIOPROTA, 2014]. The methodology is summarised in Section 3 and the illustrative examples are explored further in Section 4, building on the initial analyses reported in Appendix B. Section 5 then considers the relationship between conceptual and mathematical modelling of the GBI, building on the discussions at the second Workshop [BIOPROTA, 2014]. An overall discussion of the work undertaken in the project and of how this area of investigation might be developed further in the future is provided in Section 6. References to the main text are included as Section 7. Appendices A and B each have their own separate reference lists. The contributors to the report and their respective organisations are listed in Appendix C.

1.4 A NOTE ON NOMENCLATURE

As should be clear from Section 1.1, there is a degree of ambiguity as to what is meant by the geosphere-biosphere interface. Neither the term geosphere-biosphere interface (GBI) nor the term geosphere-biosphere subsystem (GBS) is entirely satisfactory. GBI could be understood as a boundary between the geosphere and the biosphere across which fluxes of water and contaminants are transferred, rather than as a 3D region in which a characteristic set of processes operate. GBS could be taken to imply a quasi-independent domain that is only weakly coupled to the geosphere and biosphere, whereas, in practice, strong couplings are likely to exist. In the remainder of this report, the term GBI is used, but this should always be understood to refer to a spatially extensive, 3D domain that can overlap both the geosphere and biosphere domains, and that may be strongly coupled to those domains through a variety of processes. Furthermore, it is primarily a modelling concept that is of potential utility in developing conceptual and mathematical models relevant to long-term safety assessments of disposal facilities for solid radioactive wastes, but that will not necessarily be the most appropriate approach to modelling in a specific assessment context.

2. TYPES OF GEOSPHERE-BIOSPHERE INTERFACE USED IN PREVIOUS ASSESSMENTS

In Appendix A, a review is provided of how the GBI has been represented in assessments undertaken by RWMD in the UK for deep disposal in various generic host rock environments, by the US Department of Energy in respect of Yucca Mountain, by SKB and Posiva Oy in relation to proposed KBS3-type repositories for spent nuclear fuel, by Andra (France) for disposal in clay, by NWMO (Canada) for a deep repository for low and intermediate level wastes and by Nagra for deep geological disposal of various waste types. Thus, a wide range of deep disposal concepts and host environments have been addressed.[a] Following from this review, it was determined that the greatest interest is in representing the GBI during unglaciated (boreal through to subtropical) conditions. This arises for several reasons including:

- The projected protracted duration of the current interglacial episode out to 50,000 years or more after present;
- Regulatory requirements applicable to the semi-arid environment at Yucca Mountain, Nevada in which global glacial episodes would primarily affect infiltration and irrigation requirements, but there would be no effects due to permafrost or the presence of ice sheets local to the site;
- A determination that the largest radiological impacts from a KBS3-type facility would occur during interglacial periods, albeit those occurring several hundred thousand years after present during future glacial-interglacial cycles;
- A regulatory requirement to address only the next few millennia in quantitative biosphere modelling;
- A site location beyond the boundaries of the ice sheets, though subject to frozen-ground effects and permafrost.

However, within the overall context of interglacial conditions, there are a wide variety of GBIs that require consideration. These broadly divide into two classes, i.e. those associated with wells and those associated with groundwater discharge.[b] In the case of wells, there is little evidence that the time development of the environment needs to be taken into account, but for groundwater discharge the timescales of landscape development may be comparable with the timescales over which radionuclides move through the GBI and an explicit representation of that landscape development may be required.

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[a] The programme of work that Ciemat is undertaking on behalf of ENRESA was not included in the review. The focus of this work is on low and intermediate level waste disposal within a near-surface facility at El Cabril. This work has a focus on climate change and its incorporation in performance assessments. It is being used as an input to MODARIA Working Group 6 and is not discussed further herein.

[b] This project focused primarily on radionuclide transport in groundwater. However, with some repository concepts, transport of radionuclides (notably C-14) in a free gas phase (with the bulk gases typically being hydrogen, methane and carbon dioxide) is of relevance. As this matter is being addressed in detail in an ongoing BIOPROTA programme on C-14, the role and characteristics of the GBI in relation to gaseous releases is not addressed in this report.

This leads to the need to develop rules for mapping radionuclides from one component of the environment to a different component as the landscape changes.

In many circumstances, it will be appropriate to define the GBI to encompass the whole region down from the ground surface to some depth in the host rock. However, it was noted that, in other contexts, it may be useful to focus on a region with an upper boundary some distance below the ground surface, so that the focus is on hydrogeological, hydrogeochemical and geomicrobiological processes. In this context, it was emphasised that further work is required on characterising and modelling geomicrobiological processes of relevance.

2.1 GENERIC TYPES OF GEOSPHERE-BIOSPHERE INTERFACE APPROPRIATE TO WELLS

The general approach has been to consider wells with relatively low abstraction rates, suitable for supplying water to a small number of people, but with enough capacity to encompass uses of water for domestic purposes, plant irrigation and the watering of animals. Thus, for example, RWMD cites well abstraction rates of 1,560 to 7,300 $m^3\ a^{-1}$ (4.3 to 20.0 $m^3\ d^{-1}$). However, in semi-arid conditions, with extraction of water from a substantial depth, larger extraction rates have been proposed. For Yucca Mountain, the extraction rate prescribed by regulation is 3.7 $10^6\ m^3\ a^{-1}$ (1 $10^4\ m^3\ d^{-1}$).

Wells with low abstraction rates may be either dug wells down to depths of a few metres or boreholes drilled down to depths of a few tens of metres. However, boreholes constructed for industrial water use or commercial agricultural purposes may go down to greater depths (~ 200 m).

Domestic wells may have sufficiently small abstraction rates to only constitute a minor perturbation to the flow in the aquifer from which the water is abstracted. However, wells with larger abstraction rates may give rise to significant drawdown in their vicinity. Furthermore, the degree of drawdown will depend on the recent pattern of pumping of the well. As pumping rates are likely to vary, the GBI around a well with a significant degree of drawdown is likely to be transient.

With deep wells and large abstraction rates, there will be a substantial inflow of water from the aquifer towards the well. Some of this water may be drawn up from deeper than the depth of termination of the well, so a contaminant plume may get drawn up from greater depth and captured by the well.

For abstraction from an unconfined aquifer, conditions near the surface are likely to be oxic, but conditions below the water table are likely to be reducing. With time-dependent pumping rates, there will be both fluctuating hydrological and hydrochemical conditions in the vicinity of the well. Whereas shallow wells may primarily abstract recent meteoric waters, deeper wells may abstract a mixture of waters of different chemical composition and radionuclide content. The mix obtained will depend not only on the hydrochemical depth profile, but also on the depth intervals of the well that are screened.

Wells may also be introduced into confined aquifers. In this case, drawdown will not be an issue unless the abstraction rate is excessively large. However, flows will be focused on the well, as in the case of an unconfined aquifer.

In the above discussion, it is assumed that the types of well of relevance would abstract water from either an unconfined or a confined regional aquifer. In principle, wells can also abstract perched water. However, the amounts of water likely to be available will be limited and the sustainability of such wells will be doubtful. Furthermore, as the focus of interest is on contaminated groundwater upwelling from depth, the degree of contamination of perched water bodies is likely to be limited. Therefore, attention is here concentrated on wells that penetrate to below the depth of the local water table. However, unless cased through the overlying formations, they may also capture some perched water, which is likely to be of recent meteoric character.

A wide variety of rock types may host aquifers. In general, well construction would only be down to a depth sufficient to provide the requisite yield of abstracted water (recognising that the logistics of drilling might lead to a somewhat greater depth being drilled as a precautionary measure, if the drilling rig was available on site for longer than necessary to achieve the minimum acceptable depth of drilling).

From the assessment studies undertaken to date, the following aquifer host rocks are identified as requiring consideration:

- Sands, gravels and weathered breccias typically overlying a stratum of lower hydraulic conductivity;
- Weathered sandstone;
- Limestone;
- Volcanic alluvium and other types of alluvial deposits;
- Fractured hard rock (see, e.g. Figure A.11, where the aquifer is formed from a combination of sheet joints and gently dipping deformation zones).

More generally, the well may penetrate an aquifer where flow and transport can be described using a continuum approach or an aquifer where a discrete fracture network approach is more appropriate. In either case, consideration needs to be given to potential interactions between contaminant transport in the flowing porosity and diffusion into static pore water within the rock matrix. For fractured hard rock, consideration also needs to be given to the effects of fracture minerals on contaminant transport. Combining the above considerations, various generic types of well are proposed. These are set out in Table 2.1.

<table>
<tr><th>Well Type</th><th>Well Depth (m)</th><th>Aquifer Type</th><th>Screened Interval</th><th>Abstraction Rate ($m^3 d^{-1}$)</th><th>Water Use</th></tr>
<tr><td>Dug</td><td>1 to 10</td><td>Alluvium, sand, gravel</td><td>Most of well depth below about 1 m</td><td>< 5</td><td>Domestic, irrigation of a garden or smallholding</td></tr>
<tr><td rowspan="2">Shallow borehole</td><td rowspan="2">10 to 40</td><td>Weathered sandstone, limestone, deep alluvium</td><td rowspan="2">From a few metres or just below rockhead to the bottom of the borehole</td><td>4 to 20</td><td rowspan="2">Domestic, irrigation of a garden, smallholding or agricultural crops, animal drinking water</td></tr>
<tr><td>Fractured hard rock</td><td>Strongly dependent on yield from fracture system, but probably from 4 to 20</td></tr>
<tr><td>Deep borehole</td><td>40 to 200</td><td>Weathered sandstone, limestone, deep alluvium*</td><td>From just below rockhead to the bottom of the borehole</td><td>~ 1 10^4</td><td>Commercial agriculture or for industrial process water</td></tr>
</table>

Note: *Fractured hard rock is considered less likely, as the degree of fracturing and availability of groundwater is likely to decrease strongly with depth in areas likely to be selected for radioactive waste repositories.

Table 2.1: Proposed Generic Types of Well

The dug well would access a mix of recent meteoric water and upwelling groundwater. Conditions would be expected to be oxic and little drawdown of the water table would occur. The shallow borehole would also access a mixture of meteoric water and upwelling groundwater. Both oxic and reducing waters might be abstracted, but there might also be a perturbation to reducing conditions at depth, as a consequence of atmospheric oxygen entering down the borehole. The degree of drawdown would be moderate and variable, assuming that the aquifer was unconfined. However, it is possible that the aquifer might be confined, e.g. weathered sandstone beneath confining Quaternary deposits. The deep borehole might be into an unconfined aquifer, e.g. deep alluvium, or into a confined aquifer. In either case, a mixture of groundwaters of differing chemical composition and redox characteristics would be abstracted. For an unconfined aquifer, drawdown might be profound and time-dependent on seasonal and inter-annual scales (e.g. determined by irrigation demand), leading to changes in redox conditions at depth and the mix of waters entering the well.

2.2 GENERIC TYPES OF GEOSPHERE-BIOSPHERE INTERFACE APPROPRIATE TO UPWELLING GROUNDWATER

In the case of upwelling groundwater, the areas of interest will generally be topographic lows in the landscape. However, such topographic lows may arise from various causes, e.g. they may be associated with structural characteristics such as deformation zones in hard rock or they may be incised valleys. The near-surface flow pattern may differ depending on the type of discharge area. With an incised valley, the aquifer stratum will be intersected by the incision. This can lead to a spring or seepage line along the hillslope or a discharge to a stream channel and associated riparian areas at the base of the hillslope. In either case the upwelling contaminated groundwater will mix with more recent meteoric water in the near-surface and surface environments.

With a structurally controlled low, the contamination may discharge into the bottom of the low, e.g. if it is a brittle deformation zone. As discussed by both SKB and Posiva, this can be to the regolith underlying a variety of different types of biosphere objects, including marine bays, lakes, mires and agricultural land. Mixing of the contaminated water with recent meteoric water can occur in the regolith, in the overlying sediments or in surface water bodies.

The most appropriate interface to use will be governed by the following considerations.

a) There should be a flow path through the underlying geosphere that should either be through an aquifer that can be treated as a continuous porous medium or through a complex of interconnecting fractures that may, or may not, be lined with fracture minerals.

b) The geosphere flow path may discharge directly to soils, to a spring line or to a surface water body such as a river or lake. These cases are of rather limited interest, as the radionuclide flux from the geosphere discharges directly into a component of the biosphere that is represented in conventional models of the system. However, the case of discharge to soil may merit some attention, as there is the potential for important temporal changes in hydrogeochemical conditions in the zone where upwelling groundwater mixes with meteoric water.

   Seasonally, and in response to individual precipitation events, the water table will vary over a significant range. This variation will, in itself, cause radionuclides to move up and down the soil column. At and below the water table, water and contaminant movement will be predominantly sub-horizontal and the water will emerge at the surface over a discharge area that shows seasonal and event-driven variations. There may also be sub-horizontal flows in the vadose zone above the water table, if there is significant anisotropy or textural variation in the soil, e.g.

clay layers. However, in general, water movement in the vadose zone in most soils would be expected to be sub-vertical.

At any time and location on the hillslope, it is anticipated that there would be a transition from oxidising conditions above the water table to reducing conditions below it. This transition might occur mainly across the capillary fringe, where the soil is close to saturation. During precipitation events, infiltration will percolate downward through the soil column raising the height of the water table and between such events evapotranspiration will occur, distributed over the depth of the plant rooting zone. Surface runoff may be of significance in contaminant transport. This may occur either from the area where the water table intersects the ground surface or from upslope areas where the precipitation intensity exceeds the infiltration capacity of the soil. This runoff may be distributed as sheet flow or localised in gully flow.

As a result of changing hydrological and redox conditions, contaminant transport characteristics will vary with time. Thus, rates of sorption and desorption to soil solids will vary. However, the rapidity of variations in soil moisture and redox conditions may mean that an equilibrium representation of factors affecting contaminant transport cannot be adopted. Therefore, an explicitly kinetic approach may be required. Furthermore, there may be hysteresis between the wetting and drying phases of precipitation events or seasonal cycles that needs to be taken into account.

A further consideration in northern latitudes is that seasonal freezing of the soil zone may occur. Ground freezing decreases water movement, may expel solutes from the water as it freezes and can have mechanical effects on the soil structure. It may be desirable to include a consideration of these seasonal freezing effects in definition of a soil GBI.

c) The GBI may overlie an area of discharge from the geosphere to a regolith underlying a variety of superficial features.

The groundwater discharge area might comprise upwardly directed flow through a porous aquifer rock such as sandstone, limestone or chalk, or the intersection of a fracture zone in hard rock with the overlying weathered rock or regolith.

Water flows in the weathered rock or deep regolith will have an upward component inherited from the underlying groundwater discharge area. However, there will be interactions with the percolating meteoric water resulting in vertical hydrochemical gradients and the induction of a horizontal component of water flow that is responsive to the overlying topography. Thus, the groundwater discharge area and water composition at the interface between the deep regolith/weathered bedrock and the superficial features will differ from the composition and area at the interface between the geosphere and the weathered rock or deep regolith.

Groundwater and contaminants emerging from the weathered rock or deep regolith into the superficial features will tend to be subject to more localised flow regimes and discharge environments. Thus, for example, discharges may occur to a surface water body and its immediate environs (e.g. a lake or river/stream), a stream channel where only ephemeral (seasonal) flows occur, or to a seepage area.

Based on the discussion set out above, various types of GBI are suggested as deserving of consideration. These are set out in Table 2.2.

Geosphere Type	Release via deep regolith or weathered rock	Nature of deep regolith or weathered rock	Type of release	Comment
Porous aquifer	No	Not applicable	Spring line	Not of interest. Water composition and radionuclide content similar to that in the deep groundwater, so no GBI issues of interest arise.
			Surface water body (stream, river, lake)	Of marginal interest. Water composition and radionuclide content determined by the mixing of aquifer water with stream, river or lake water. Can use a simple dilution calculation plus a mixing model for chemical speciation.
			Seepage zone	Of marginal interest, but rather more complex than the case of direct discharge to a surface water body. Water composition determined by interaction of aquifer water with meteoric water in the presence of soil solids in the seepage zone. Water would move downslope either as subsurface flow or surface runoff to reach the local drainage network. Further dilution and changes in composition would occur when it entered the surface water body. Limited range of land uses of the seepage zone.
			Soil	Of interest. Complex patterns of flow and transport in the soil zone, with seasonal and event-driven changes of relevance. Considerable modifications in water composition in moving from reducing to oxidising conditions. It is possible that kinetic effects could have significant influence on transport. Downslope movement of water and contaminants in the soil zone may require consideration, with progressive interactions with meteoric water during this transport.
Fault Zone	No	Not applicable	Spring line	Comments are similar to those for a porous aquifer. If a fault zone from hard rock outcrops at the surface, as is implied by the lack of deep regolith or weathered rock, there is unlikely to be a deep soil layer present. Therefore, the interface with soil is of less interest than if a porous aquifer is the source of contaminant discharge.
			Surface water body (stream, river, lake)	
			Seepage zone	
			Soil	
Porous aquifer	Yes	Porous medium	From aquifer across deep regolith or weathered rock into the superficial features	Of interest. It is assumed that transport is entirely in the saturated zone, so this reduces the complexity of approach required. However, there will be mixing of the deep groundwater with meteoric water in a zone of complex lithology and changing chemical composition of the groundwater. Temporal variations in conditions due to seasonal or event-driven effects will be limited and can probably be neglected.
		Fracture network		Not considered relevant. Unlikely to have fractured hard rock in the weathered zone overlying a sedimentary rock aquifer.

Table 2.2: Categories of GBI for the Case of Upwelling Groundwater

Geosphere Type	Release via deep regolith or weathered rock	Nature of deep regolith or weathered rock	Type of release	Comment
Fault Zone	Yes	Porous medium	From aquifer across deep regolith or weathered rock into the superficial features	Considerations are very similar to those when the geosphere type is a porous aquifer. The main differences are likely to be in the spatial extent of the geosphere discharge and the chemical composition of the deep groundwater.
		Fracture network		Of interest. Transition from transport in a sparse network of fractures to transport in a much denser network potentially originating from a different cause (ice-sheet loading/unloading). Likely to have different types of fracture infill (e.g. calcite or clay minerals). Mixing with recent meteoric waters will occur and oxygen in meteoric waters may be depleted in the fractures over length scales of tens of metres, so the transition between oxidising and reducing conditions may be spatially extensive.
Either porous aquifer or fault zone	Yes	Porous Medium	From deep regolith or weathered rock through the superficial features to a spring line, surface water body, seepage zone or soil	Considerations are similar to those arising for direct release from a porous aquifer to these various surface environments. The main difference is that the water composition and contaminant concentrations will be modified by passage through the deep regolith or weathered rock.
Fault zone	Yes	Fracture network	From deep regolith or weathered rock through the superficial features to a spring line, surface water body, seepage zone or soil	Of interest. Complex flow paths are likely to exist in the fracture network and there may be a transition from larger-scale flow patterns to smaller-scale patterns as the influence of local topographic features will be greater closer to the surface. In addition to variations in fracture infills and oxygen consumption in the near-surface strata, there may be significant gradients in water composition due to microbial effects in superficial soils. Interactions with soils and other near-surface sediments (e.g. organic layers underlying surface water bodies) will need to be taken into account. The vadose zone may be of importance and seasonal and event-driven effects may propagate to significant depths down fracture zones of high hydraulic conductivity. This may be the most complex of the various GBIs listed as being of interest.

Table 2.2: Categories of GBI for the Case of Upwelling Groundwater (Continued)

In general, the timescales of interest when simulating radionuclide transport across the types of GBI listed in Table 2.2 will range up to a few thousand years, though longer timescales may be applicable for highly sorbed elements such as thorium and plutonium. Thus, modelling can often relate to a single broad climatic condition, such as temperate, boreal or periglacial. However, this does not exclude investigation of the effects of climatic variations within one such state. Climate varies on a variety of timescales varying from decades up to millennia (climate is typically defined over a 30 year interval, so inter-annual and seasonal variations are generally considered within the framework of a single longer-term climatic condition). Therefore, it may be of interest to investigate the extent to which a GBI would be perturbed by an extended period of variant climatic conditions, e.g. the Medieval Warm Period, the Little Ice Age, or the more extended Holocene Thermal Optimum at around 6,000 years Before Present.

As most work has been conducted on radionuclide transport under temperate conditions, frozen ground effects have only been given limited consideration. In order to address frozen-ground effects in a structured way, it might be appropriate first to consider the various GBIs under time-independent climatic conditions with seasonal ground freezing. Once this topic had been studied, it might be feasible to move on to consider how the GBI would evolve in transitions from temperate to boreal/periglacial conditions and from boreal/periglacial conditions to temperate conditions. Having studied transitions to seasonally frozen ground, it might be possible to extend the work to considerations of permafrost development. However, this is a more complex issue and impinges upon the approach to modelling the deep geosphere, as well as modelling of the GBI.

The discussion above does not address landscape evolution. Based on the various national programmes, two cases are identified as being of interest. These are valley incision in a lowland landscape and post-glacial land rise subsequent to a glaciation. The latter is of particular interest in northern latitudes and has been studied extensively by SKB and Posiva. The main issues concern the inheritance of radionuclides as environmental media alter as a consequence of the sequence of transitions coastal bay → lake → mire → agricultural land, or variants on that sequence. Overall landscape models have been developed to represent such sequences and biosphere objects have been defined as components of those landscape models.[a]

Valley incision is of interest both in the UK and French programmes. In both cases, the main interest is in fluvial incision in a lowland regime. Geomorphological studies by Nirex of the deposits laid down by the Anglican glaciation (MIS 12) and the Late Devensian glaciation (MIS 2) indicate that fluvial incision has subsequently created valleys of depths of several tens of metres below the relatively smooth original palaeosurface. As valley depths are similar in both cases, it seems that evolution towards an equilibrium valley profile is largely complete on a timescale of ten to twenty thousand years. It seems likely that significant future changes in valley profiles would occur only if there was a significant change in base level (normally sea level, but sometimes a hydraulic control upstream of the sea). If this were to occur, then the long profile of the stream or river would adjust through erosion and sedimentation such that it matched the new base level.

Overall, it seems unlikely that valley incision will significantly change the form of lowland landscapes over the remainder of the present long interglacial. In future interglacials, incision might occur into newly deposited glacial and post-glacial deposits. In such cases, the GBI might require representation of a time-dependent plume of radionuclides migrating through the new deposits in combination with the incision of a new valley into those deposits.

[a] Long-term climate change and landscape development are being investigated in detail in the IAEA MODARIA Working Group 6 programme. This aims to develop global climate scenarios of broad relevance for the long-term future, use various climate models to simulate global and regional climates under those scenarios, downscale those results to specific sites and to address the implications for landscape development at those sites. One aim of this work is to improve the consistency with which future projections of climate change are handled in different assessment contexts.

2.3 DETERMINISTIC OR STOCHASTIC MODELLING

One area that is not addressed in detail in this report is whether mathematical models of the GBI should be deterministic or stochastic. Stochastic modelling is widely used in simplified overall assessment models. However, these models are often underpinned by detailed, process-based models, with results or simplified models abstracted from these detailed models for use in assessment studies. The complexity of the detailed models means that they are typically used in deterministic mode, with the robustness of the results obtained explored in single or multi-parameter sensitivity studies. In this report, the focus is on the development of conceptual models of the GBI and how these may be translated into comprehensive, process-based mathematical models. These models would typically be used in exploratory studies to determine the principal controls on assessment results and thus to inform the implementation and parameterisation of simpler, assessment-level models.

3. PROPOSED METHODOLOGY FOR DEVELOPING A CONCEPTUAL MODEL OF THE GEOSPHERE-BIOSPHERE INTERFACE

3.1 OVERALL METHODOLOGY

Following from the first Working Group meeting, the Technical Support Team developed an overall methodology for developing conceptual models of various types of GBI. That methodology is described in detail in Appendix B and a description of it has been published in the peer-reviewed literature [Smith et al., 2013]. The overall methodology is intended to be applied within the framework of a specific assessment context, with the assessment context comprising the various components set out in BIOMASS [2003] as follows:

- Purpose of the assessment (from testing of initial ideas for a disposal concept to support for a disposal license application requiring a detailed, site-specific performance assessment against regulatory criteria);
- Endpoints of the assessment (e.g. effective dose to a representative person, radionuclide fluxes to the biosphere, absorbed dose rates to biota);
- Assessment philosophy (e.g. degree of pessimism to be adopted, extent to which stylized situations can be used as a basis for compliance demonstration);
- Repository system (including basic assumptions for waste characteristics, packaging, engineered system, and location within the host rock);
- Site context (including basic assumptions for geographical, climatic, geological and geomorphological aspects);
- Source term (in the present context, potential radionuclide fluxes entering the GBI, including consideration of their spatial and temporal distribution);
- Time frames for assessment (noting that both the source term and the endpoints of the assessment may differ among time frames);
- Societal assumptions (e.g. level of technological development, rural or urban, patterns of behaviour).

The methodology to be applied after the assessment context has been determined is summarised in three flow charts. These are shown in Appendix B, but they are reproduced here as Figure 3.1, since they are central to the following discussion.

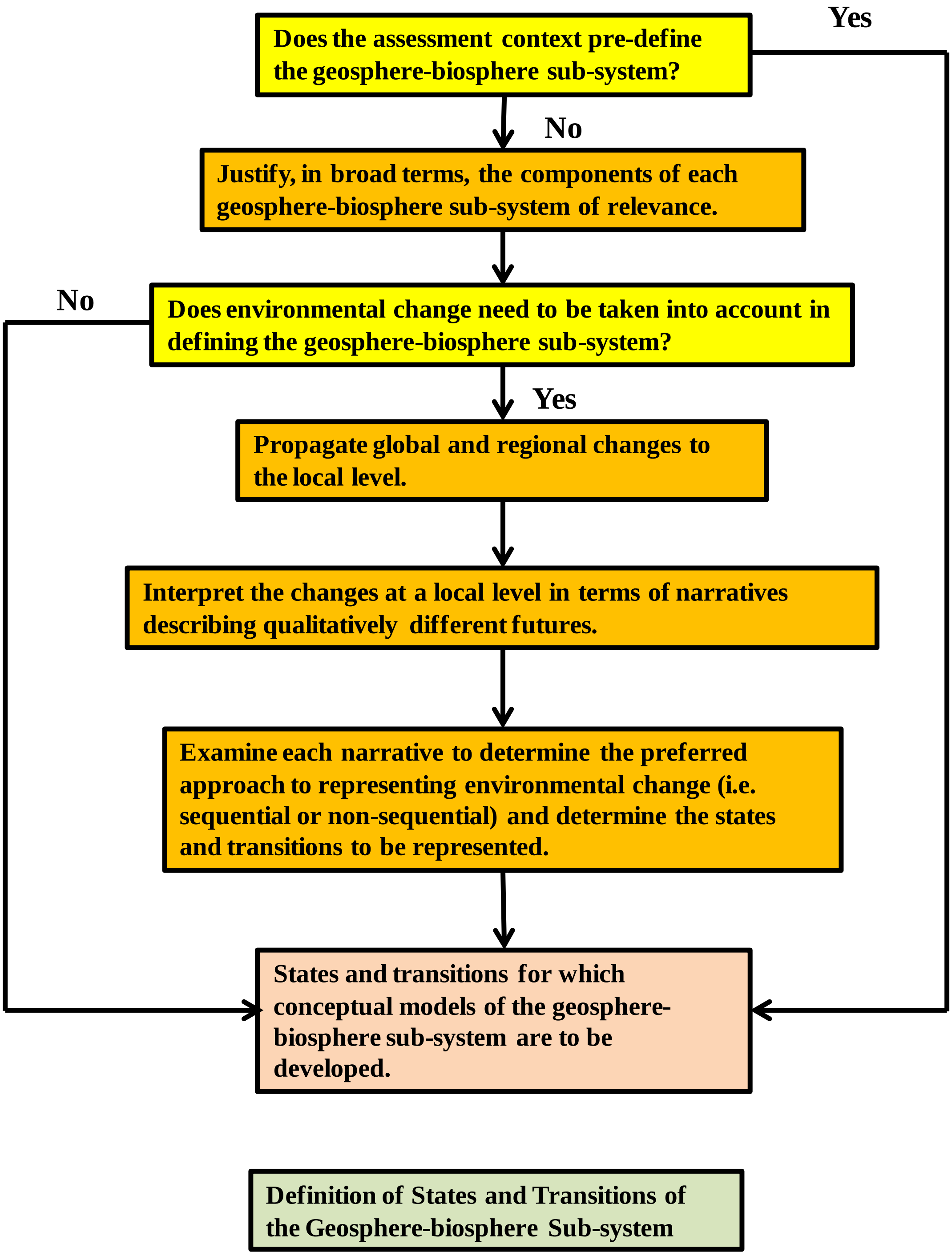


Figure 3.1a: Initial Steps in the Methodology leading to the Definition of States and Transitions of the Geosphere-Biosphere Sub-system (GBI)

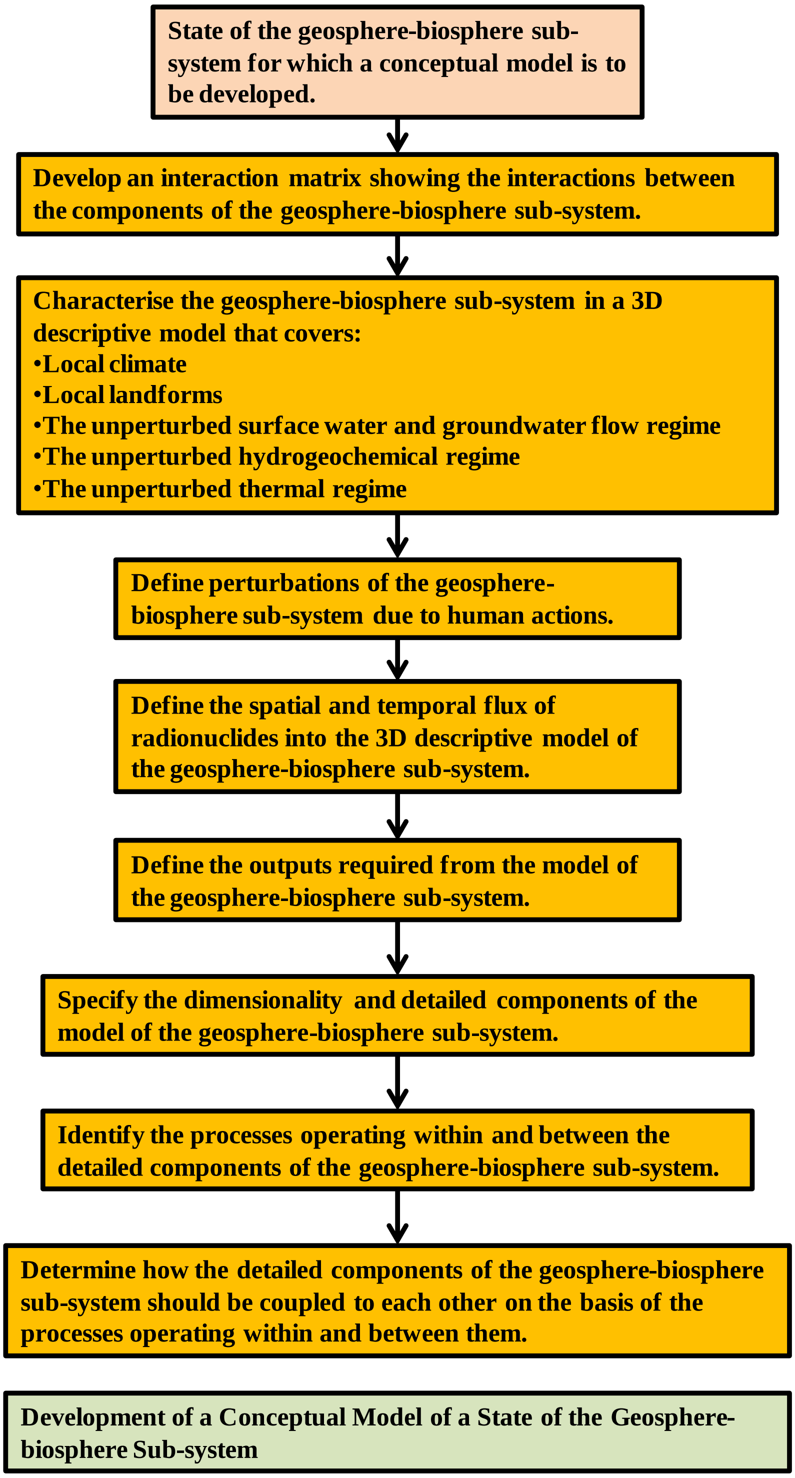


Figure 3.1b: Further Steps in the Methodology leading to the Development of a Conceptual Model of a State of the Geosphere-Biosphere Sub-system (GBI)

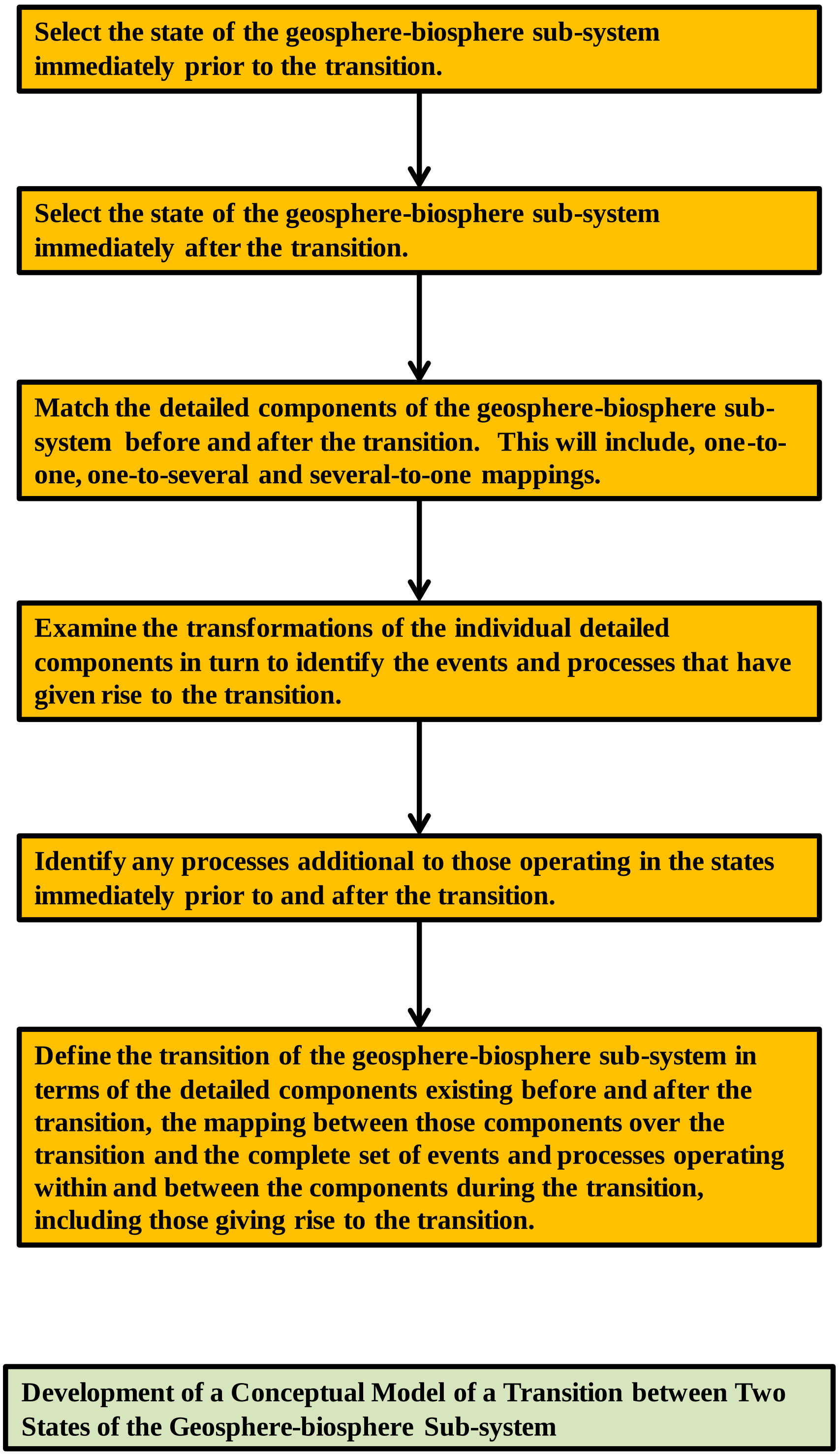


Figure 3.1c: Additional Steps in the Methodology for handling Transitions between States

It is also convenient to summarise the various stages of the methodology shown in Figures 3.1a and 3.1b in the form of a table. This is done in Table 3.1.

Table 3.1: Summary of the Methodology for Developing a Conceptual Model of the Geosphere-biosphere Sub-system (GBI)

Step	Description	Relevant Figure
1	Determine whether the assessment context pre-defines the GBI. If not, identify and justify, in broad terms, the components of each GBI of relevance.	3.1a
2a	Determine whether environmental change needs to be taken into account in defining the GBI. If so, propagate global and regional changes to the local level.	
2b	Interpret the combined effects of these changes at a local level in terms of narratives describing qualitatively different futures.	
3	Examine each narrative to determine the preferred approach to representing environmental change (i.e. sequential or non-sequential) and determine the states and transitions to be represented.	
The following steps apply to each state for which a conceptual model is to be developed.		3.1b
4	Develop an interaction matrix showing the interactions between the components of the GBI.	
5	Characterise the GBI in a 3D descriptive model.	
5a	Define the local climate.	
5b	Define local landforms.	
5c	Define the unperturbed surface-water and groundwater flow regime.	
5d	Define the unperturbed hydrogeochemical regime.	
5e	Define the unperturbed thermal regime.	
Iteration of steps 5c to 5e may be required to achieve a self-consistent description of the unperturbed system.		
5f	Define perturbations of the system due to human actions.	3.1b
5g	Define the spatial and temporal flux of radionuclides into the 3D descriptive model of the sub-system developed in Step 6.	
5h	Define the outputs required from the model of the GBI.	
6	Specify the dimensionality and components of the model of the GBI (these components are more detailed than those identified at Step 1).	
7a	Identify the processes operating within and between the components specified in Step 9 and evaluate their significance in relation to the individual components and the interactions between them.	
7b	Determine how the components of the GBI should be coupled to each other on the basis of the processes operating within and between them.	

Note that Table 3.1 does not address the methodology for development of a conceptual model of the GBI for transitions between two states of the system (Figure 3.1c). This topic has only been explored to a limited degree on the current project. In general terms, the proposed methodology for representing transitional states of the GBI follows that for representing transitional states of the biosphere in BIOCLIM [2004].

In many assessment contexts, the explicit representation of transitions will not be required, because radionuclide residence times in the GBI are short compared with the timescale for substantial changes to that sub-system. However, there will be contexts in which the time-development of the GBI is a significant consideration. To address this, time-invariant states before and after the transition of interest are fully characterised using the methodology summarised in Table 3.1. These states are characterised in terms of detailed components, and the processes operating within and between those components. Components of the sub-system prior to and after the transition are matched to each other. In some cases, there will be a one-to-one correspondence between those components, but this will not always be the case, e.g. if the transition involves emergence of a land area from the sea or the conversion of a lake to a mire. Where there is not a one-to-one correspondence, a judgement will have to be made as to how the components present prior to the transition map onto those present subsequent to the transition.

Once a mapping between the components before and after the transition has been completed, the transformations of each of the components can be examined in turn to identify the events and processes that have given rise to the transition. Many of the processes identified are likely already to be represented in the descriptions of the individual states. Thus, for example, erosion and sedimentation may be represented within a state because they affect radionuclide transport. However, in the context of a transition between states they will be identified through their effects on altering the geometry and properties of components of the GBI. Also, additional processes may be identified that are specific to the transition. These additional processes can then be included along with the processes associated with each state to provide a conceptual model of the transition. Note that the additional processes are identified because of their action in transforming the components of the GBI, but that they are included in the conceptual model of the GBI both because they transform the sub-system by performing the mapping described earlier and because they can act as additional radionuclide transport processes during the transition.

Whereas, the conceptual models for states relate to radionuclide transport through a time-invariant environment, the conceptual models for transitions represent radionuclide transport through a changing environment.

In the remainder of this section, an account is given of the various stages and steps in the methodology for defining the GBI for a single state of the system. However, a more detailed account with example applications is included in Appendix B.

3.2 STEPS IN THE METHODOLOGY FOR DEFINING A SINGLE STATE OF THE GEOSPHERE-BIOSPHERE INTERFACE

3.2.1 Stage 1: Identification and Justification of Geosphere-biosphere Sub-systems

As with the BIOMASS [2003] methodology applicable to the biosphere, the overall approach consists of up to three steps.

Step 1: Identification and Justification of Components of the Geosphere-biosphere Sub-system

In Step 1, the assessment context is reviewed to establish whether or not it pre-defines the GBI. If it does not, the components of the GBI or sub-systems to be represented are identified and justified according to an interpretation of the assessment requirements. In practice, whereas the biosphere is sometimes prescriptively defined in regulation, this would not generally be the case for any aspects of the deeper system, so it will normally be necessary to identify and justify the components of each GBI.

To a large extent, these components are similar to those for the biosphere. They comprise:

- Climate and atmosphere;
- Geographical extent;
- Location;
- Topography;
- Human community;
- Near-surface lithostratigraphy;
- Water bodies;
- Biota.

In contrast to the biosphere, there is also a need to address the issue of where the upper boundary of the GBI is set. This might be at the upper boundary of soils and sediments where they interface with either the atmosphere or surface-water bodies. However, alternatively, it could be at the base of any soils and sediments present, such that it immediately overlies deeper unconsolidated material or weathered bedrock.

It is of interest to note that this step precedes the consideration of environmental change (this occurs in Step 2, which is discussed below). Thus, the components of the GBI set out above can only be defined in broad terms, since they will be subject to modification as the climate and landscape alter. In many cases, this will pose fewer difficulties than with the biosphere, since the GBI is expected to be less affected by environmental change than the biosphere. However, in assessment contexts in which it is necessary to take account of environmental change and in which that environmental change has profound effects on the GBI, it will only be possible in Step 1 to define the GBI at the present day, deferring definition of the GBI in the future to Step 2.

Step 2: Consideration of Environmental Change

In Step 2, consideration is given to whether environmental change needs to be taken into account in defining the GBI(s). If there is no explicit guidance from the assessment context, or if the assessment context expressly requires environmental change to be considered, the following questions need to be addressed:

- what are the relevant mechanisms causing environmental change?
- what are the potential impacts of the resultant environmental change on the GBI?

As to the relevant mechanisms causing environmental change, these are the External Features, Events and Processes (EFEPs) identified in Figure B3 of BIOMASS (2003) and illustrated in Figure B.2 of Appendix B.

Identification of the potential impacts of these environmental changes on the GBI requires propagation of regional changes to the local level. This can be done by combining the regional landscape responses shown in Figure B.2 with the GBI components given previously (see Table B.1 in Appendix B).

Having identified the EFEPs of relevance in a specific assessment context and propagated their influence from a regional to a local level, there remains a requirement to interpret the combined influence of these EFEPs on the disposal system in terms of qualitatively different futures. This interpretation may make use of tools such as interaction matrices to define how the various components of the local system interact under the influence of EFEPs propagated down to the regional level and may also make use of transition diagrams, as developed in BIOCLIM [2004], to represent the time-evolution of the components of the GBI in relation to each other. However, the overall aim is to provide narratives describing the various qualitatively different futures, as these narratives provide the key input to Step 3 of the identification and justification process.

Step 3: Examination of Narratives of Environmental Change

In Step 3, each narrative is examined to determine the preferred approach to representing environmental changes that affect the GBI in an assessment. In making such a decision, account has to be taken of the narrative itself, the overall assessment context, and decisions that are being made as to how other parts of the disposal system are to be represented, e.g. if the biosphere is assumed to be time-independent over a particular interval, it may difficult to match it to a time-dependent GBI, so it may be preferable to adapt the approach such that both the biosphere and GBIs are either time-independent or time-dependent.

As with the biosphere [BIOMASS, 2003], the main choice in modelling approaches is between a non-sequential and a sequential approach. In the non-sequential approach, the judgment is made that, taking account of the narrative description of projected environmental changes at the regional and local scales, it is possible to identify a finite number of discrete, quasi-equilibrium states of the GBI that are adequately representative of key stages in the narrative. It is further judged that time-invariant models for each of these states can then be developed and applied independent from one another, with their projected sequence disregarded. This approach requires that radionuclide distributions in the GBI and fluxes from that system to the biosphere during any particular state are not strongly influenced by radionuclide fluxes that entered the GBI prior to the occurrence of that particular state.

In the sequential approach, the separation into non-interacting states is judged invalid, unnecessary or otherwise inappropriate. Thus, the GBI is represented either through simulating a sequence of discrete states or via quasi-continuous variations of the properties and characteristics of GBI components [see BIOMASS, 2003]. An intermediate position is advocated in BIOCLIM [2004], according to which the analysis relates to a sequence of states and also addresses the effects of the periods of transition between these states. In this approach, the characteristics of the time-independent states are first defined on a component-by-component basis. Following this, transitions between any pair of states are characterised by describing how the characteristics of the components alter over the transition from those of the pre-transition state to those of the post-transition state.

Although a non-sequential approach can often be justified for the biosphere (due both to the short residence times of key radionuclides and the need to make broadly based judgments as to its characteristics), such an approach is more difficult to justify for the GBI. Radionuclide residence times in this zone are likely to be more protracted than in the biosphere and its time development is likely to be more constrained by its physical and chemical characteristics than that of the biosphere. Indeed, the underlying narrative of environmental change will imply a corresponding narrative as to how the GBI alters with time. Thus, it seems likely that a sequential approach to geosphere-biosphere representation will be preferred. However, this leaves open the issue as to whether that representation should be continuous or discrete. In a continuous approach, radionuclide transport would be modelled through a continuously changing environment. In practice, this would imply the setting up of a set of linked differential equations representing both environmental change and radionuclide transport. In the discrete approach, radionuclide transport could be modelled as occurring within a fixed environment during each state of the GBI. However, rules would need to be provided to map the radionuclide distribution present at the end of one state to the radionuclide distribution at the beginning of the next state. Those rules would reflect two considerations:

- The processes involved in causing the GBI to move from one state to another (e.g. transformation of a lake to a mire by terrestrialisation);
- The model structures adopted for the two states (e.g. requiring radionuclides present in the soil/sediment column to be reassigned from the layers defined before the transition to the layers defined after the transition).

Thus, mapping rules depend on both the changing characteristics of the sub-system and the way in which those changing characteristics are represented in the adopted model of the sub-system.

Transitional regimes and transitions from one state to another will be of particular importance if radionuclides can first be accumulated in, and then released from, particular environmental media. Specific processes and system elements that could lead to accumulation include: the presence of sharp gradients, such as saline fronts, changing redox conditions and the presence of organic matter; presence of hyper-accumulator plants; release to wetlands subject to rapid biological turnover and sediment accumulation. Differential effects of accumulation for successive radionuclides in a decay chain (such as that of U-238) can lead to gross departures from secular equilibrium that need to be taken into account.

3.2.2 Stage 2: Description of Geosphere-biosphere Interface

Outputs from Stage 1 of the methodology set out in Section 3.2.1 are narratives of environmental change and a determination as to whether each of those narratives should be interpreted in terms of a continuously changing GBI, a sequence of periods with a GBI defined for each, or just a single time-independent GBI. Here, it is assumed that each narrative is decomposed into a sequence of periods on the principle that, if the GBI is described for each such period, then a continuous account can be created by taking these descriptions and combining them to generate descriptions of the transitions between periods.

At the beginning of this stage, the components of the GBI are already defined (climate, atmosphere, topography, near-surface lithostratigraphy, water bodies, biota). For a particular stage in a narrative, these components need to be characterised in specific terms and their inter-relationships need to be identified. This can be done through the use of an interaction matrix (see Figures B.3 and B.4).

The interaction matrix developed at this step (Step 4) goes beyond a listing of processes linking the various lead diagonal elements, as it briefly describes the key considerations determining the interactions, recognises important indirect effects and notes interactions occurring at the regional scale, as appropriate.

Once the GBI has been described in terms of an interaction matrix, it can be analysed more fully in terms of the geometrical relationships of the individual components, the spatially distributed properties of those components and the processes through which the various components affect their properties, either within a component or as a consequence of interactions between components.

3.2.3 Stage 3: Characterisation of the Geosphere-biosphere Interface

An interaction matrix developed as described in Section B.1.2 provides a basis for a description of the GBI that is suitable for use in developing a mathematical model of the sub-system. This requires consideration not only of the components of the sub-system, but also their geometry, their spatially distributed properties and the processes that operate within and between them. In order to achieve this description, the following sequence of steps is identified.

Step 5: Define the GBI

5a) Define the local climate that will exist over the period for which the GBI is to be modelled;

5b) Define the local landforms that will be present over the period for which the GBI is to be modelled. This includes both their topography and their lithostratigraphy, since the two are intimately related.

5c) Characterise the unperturbed surface-water and groundwater flow regime that would apply under the specified climatic and landform characteristics.

5d) Characterise the unperturbed hydrogeochemical regime that would apply under the specified climatic and landform characteristics, and with the specified surface-water and groundwater flow regime.

5e) Characterise the unperturbed thermal regime that would apply under the specified climatic and landform characteristics, and with the specified surface-water and groundwater flow regime.

5f) Specify how human actions are assumed to perturb the system.

5g) Define the spatial and temporal pattern of radionuclide fluxes that would enter the GBI over the period for which it is to be modelled. This needs only to be done to the extent that it influences the way in which the mathematical model of the GBI would have to be formulated in order to utilise that spatial and temporal pattern as input.

5h) Define the outputs that are required from the GBI, e.g. spatially and temporally variable radionuclide fluxes to the biosphere or concentrations in environmental media such as soils and surface-water bodies.

Once steps, (a) to (h) have been completed (including iterations between them to achieve self consistency, as required), it will be possible to provide a conceptual description of the GBI from which a mathematical model can be developed, or against which an existing mathematical or computational model can be audited in terms of its fitness for purpose (see below). Having developed such a model, it will be possible to perform the following steps.

Calculate the transport of fluxes of radionuclides entering the GBI in order to estimate either output fluxes to the biosphere or output concentrations in environmental media.

Calculate radiation doses and other measures of radiological impact (a step that lies outside the development and application of a model for the GBI).

In the following, consideration is given to how steps (a) to (h) should be undertaken in practice for each of the GBIs that need to be addressed in each scenario developed as part of the assessment process.

Step 5a: Defining the Local Climate

The local climate can seldom be defined more closely than in terms of a Köppen-Trewartha climate state. However, for assessment modelling of the hydrological and hydrogeological aspects of the GBI, temperature and precipitation data will be required. For the representation of potential future climatic conditions, it will not be possible to specify these data very precisely and mean monthly values have previously been used.

From mean-monthly temperature and precipitation values together with limited assumptions concerning the effects of different soil and vegetation types on evapotranspiration, assessments can be made of the annual hydrologically effective rainfall (relevant to computing the water balance for the area of interest) and of the summer soil moisture deficit (relevant to irrigation requirements). For a local area, it will generally be adequate to define temperature, precipitation and other, climate-related variables each as a single time series applying to the entire area. However, if there is substantial local variability in factors such as altitude and aspect, it may also be necessary to define spatial variations in each of the relevant quantities. Also, whereas for many calculations, the use of long-term averages of the various quantities will be appropriate, in some cases it will be appropriate to take into account the inter-annual variations that are recorded in the records from the analogue stations or are simulated by climate models. For example, it may be appropriate to calculate the summer soil moisture deficit on a year-by-year basis in order to determine the fraction of years that would give rise to an irrigation requirement under a specific irrigation scheme.

Step 5b: Defining Local Landforms

As noted above, this includes both the overall topography and the lithostratigraphy. Where a site has been selected, such a characterisation would typically comprise a 3D visualisation of the topography and lithostratigraphy either of the existing landscape or of the landscape evolved under particular assumptions. Even if a generic assessment is being undertaken, it will generally be appropriate to develop an illustrative 3D visualisation of the landscape, so that a suitable abstraction of that landscape can be made for modelling purposes. It is emphasised that the visualisation of the landscape in 3D is for the purposes of conceptual model development. It does not imply that the mathematical model to be derived from that visualisation would necessarily be 3D. This would depend on the assessment context and the degree of homogeneity both in the landscape and in the pattern of radionuclide releases to the GBI for which the assessment was to be undertaken.

Although the GBI may not extend to the ground surface, it will generally be appropriate to define local landforms from the surface to a depth in the bedrock below the interface with the geosphere component of the system. In this way it will be ensured that the GBI is consistently embedded within the wider modelling framework.

The 3D visualisation of the landscape will usually comprise a set of components, each with a well-defined geometrical extent and arranged in a space-filling arrangement, such that there are no gaps in that arrangement between the ground surface and the base of the representational domain within the lateral extent over which that representational domain is defined. Each of those components will be defined by a set of properties. Those properties would be defined in terms of parameter values or parameter value distributions at the mathematical model stage. However, for developing a conceptual model, it is sufficient to recognise the types of properties that would be required to characterise each component.

Step 5c: Defining the Unperturbed Surface-water and Groundwater Flow Regime

To a large extent, the climate and topography will define the surface-water and groundwater flow domains, though account may also have to be taken of regional sources of surface water and groundwater. Thus, for example, if a river passes through the modelled domain, account will have to be taken of the upstream source of water in this river and the downstream loss of water in this river from the domain. Similarly, if the domain is underlain by a regional aquifer, then both discharge from and recharge to this regional aquifer within the model domain will need to be taken into account. At the conceptual modelling stage, the aim is only to describe the overall pattern of surface-water and groundwater flows within the GBI domain, rather than to quantify those flows. However, it is recognised that it may be necessary to undertake some quantitative flow or water-balance modelling in order to obtain the insights necessary for developing a conceptual model of the flow system, e.g. to determine those areas that constitute discharge zones and those that constitute recharge zones at different seasons of the year.

In defining the groundwater flow regime, the information required is primarily the hydrological properties of the materials present in the domain and the geometrical relationships of those materials to each other. To this information must be added information on the local climate, which is necessary for estimating both surface water flows and infiltration. Finally, surface water and groundwater flows across the lateral boundaries of the modelled domain need to be established from information available at a regional scale.

The surface-water and groundwater flow regime is defined as that appropriate to the unperturbed state. Definition of this state is not unambiguous, as it necessarily takes account of the pattern of land use in the local area. Here it is defined as meaning that no wells are present in the local domain of the GBI and that no large-scale engineered hydrological structures (such as dams or reservoirs) are present. If such features are currently present, then account must be taken of their perturbing effects when defining the postulated unperturbed flow regime. The reason for adopting this approach is that such perturbing features may not be present in the future at times of relevance to the assessment. Of course, if these features are considered to be relevant to the assessment process they can be restored at step (f).

Step 5d: Defining the Unperturbed Hydrogeochemical Regime

The hydrogeochemical regime may be defined mainly by observations or by model simulations in which waters of different types are mixed in the GBI domain and react with the various types of solid that are present. Although model simulations may be undertaken at this stage, the main aim is to characterise the spatial distribution of different water types present in pore and fracture spaces in the sediments and rocks that are present in the domain. As with the flow regime, it is the unperturbed state that is considered, so the modifying effects of existing perturbations due to wells and large-scale engineered hydrological structures have to be allowed for so as to characterise the unperturbed situation. In addition, any large-scale chemical perturbations, e.g. due to contamination, should also be allowed for, but this does not include effects such as typical fertiliser additions associated with the specified land use (if that land use is similar to that at the present day).

Pore and fracture waters will typically be defined in terms of their major and trace element composition, and in terms of other derived quantities such as pH and redox potential. At the conceptual stage, it is likely to be appropriate to describe these waters as broad types, rather than give detailed compositions. An important aspect of the conceptual model will be the spatial distributions of these different water types relative to the various solid media that are present.

It should be noted that the process of developing the hydrogeochemical model may identify aspects of the hydrological and hydrogeological model that need to be updated. Thus, there may be a degree of iteration between items (c) and (d). Such iterations may also involve the acquisition and interpretation of additional data in order to resolve inconsistencies or ambiguities identified in the process of model development.

Step 5e: Defining the Unperturbed Thermal Regime

In the GBI, radioactive decay heat originating from the repository is unlikely to be a significant consideration. Therefore, the thermal regime will be largely determined by the interplay of climate conditions and geothermal heat production. In broad terms, the types of thermal regime to be considered include unfrozen, seasonal ground freezing, discontinuous permafrost with taliks and continuous permafrost with taliks. Where permafrost is present, there will also be an overlying active layer that is subject to freeze-thaw processes.

In the active layer, there will be a need to characterise seasonal fluctuations in temperature and extent to which the water present in that layer will be frozen or unfrozen. As freezing will affect the hydraulic properties of the material and the freezing point will be influenced by the chemical composition of the pore and fracture water, the thermal regime will have a strong influence on the hydrogeological and hydrogeochemical regimes. Therefore, it will be appropriate to have the thermal regime in mind when defining those hydrogeological and hydrogeochemical regimes. This applies even more strongly when permafrost regimes are under consideration, as these will result in reorganisation of the groundwater flow system at a regional scale relative to that which would exist in unfrozen conditions. Nevertheless, detailed consideration of the thermal regime is placed in sequence after the hydrogeological and hydrogeochemical aspects of conceptual model development. This is because it is primarily determined at the regional scale (and hence provides part of the context for the totality of conceptual development of the GBI), whereas here the consideration is its conceptual model implications at a local scale. This emphasises that all stages of conceptual model development relating to the GBI take place within a predefined regional context.

Step 5f: Perturbations due to Human Actions

Once an unperturbed system is fully defined, it is possible to impose potential human actions upon it. In general, these human actions will comprise the construction and utilisation of water wells and boreholes constructed for other purposes (such as the exploitation of geothermal energy). Injection boreholes may also need to be considered, although these would typically introduce water to considerable depth (e.g. in fracking or in recycling of geothermal water after heat extraction) and might not significantly influence the GBI). Other large-scale human activities may also need to be considered, e.g. quarrying or reservoir construction and utilisation. However, general land-use in the sub-model domain would not need to be considered, as this would be addressed in the conceptual model of the unperturbed system.

It is anticipated that the relevant human actions would be prescribed in the scenario under consideration and would be strongly determined by the assessment context. Thus, in the context of developing a conceptual model of the GBI, the emphasis is on characterising the effects of such perturbations and not in justifying the types of perturbations to be considered.

In general, when considering the effects of human actions, the same sequence can be considered as in defining the unperturbed system, i.e. the first consideration is effects on the geometry of the system (topography and lithostratigraphy), then the effects on hydrology and hydrogeology, and finally effects on hydrogeochemistry. Effects on the thermal regime may need to be considered outside this sequence. For example, if large-scale ground thawing were to occur, this would need to be considered before effects on hydrology and hydrogeology were addressed.

Step 5g: Spatial and Temporal Patterns of Radionuclide Flux

The preceding steps will result in a 3D description of the GBI. This provides a context for specifying the spatial and temporal pattern of radionuclide flux entering that sub-system, generally across its bottom boundary. That radionuclide flux will generally be provided by a model of the deeper part of the geosphere. However, the spatial domain of that model may overlap with that of the GBI, so the flux to be extracted may come from an internal surface within the geosphere model, rather than from its upper boundary. In addition, the flux may not be fully characterised in space and time, e.g. it may be a time-dependent flux arising from a 1D (stream tube) representation of the geosphere. If this is the case, additional assumptions may have to be made in order to map it onto a spatially extensive boundary. Alternatively, the lack of spatially distributed information may be a consideration in determining the structure and dimensionality of the model of the GBI.

Step 5h: Outputs from the Model of the Geosphere-biosphere Sub-system

Outputs from the GBI will typically be either radionuclide fluxes used as input by a biosphere model or radionuclide concentrations in environmental media. In either case, spatially distributed values are likely to be required.

Step 6: Defining the Dimensionality and Structure of the Conceptual Model

Having defined the GBI in 3D through steps 5a to 5h, it is appropriate to give consideration to the dimensionality in which it needs to be modelled and the structure of the model at the selected dimensionality.

The dimensionality of the adopted model will depend on the characteristics of the GBI and also on the assessment context. For example, if the assessment context only requires spatially averaged radionuclide concentrations in environmental media, then a lower dimensionality may be appropriate than if there is a requirement to define peak concentrations in space and the spatial extent of concentrations that are more than a particular fraction of those peak concentrations.

The dimensionality of the model can also depend on how the radionuclide flux entering the model domain is defined. For example, if the input flux is spatially distributed over a relatively homogeneous domain (such as the base of a deep agricultural soil directly overlying a bedrock aquifer that is modelled as part of the geosphere), then a 1D vertical model of the soil may be appropriate to map that flux into radionuclide concentrations at the soil surface (though sub-horizontal transport in the soil column may have to be represented as a loss process from the system) or a 2D hillslope model may be used to explicitly include downslope transport to a river channel. In contrast, if the input flux is defined without any information on its spatial extent (as with a stream tube representation of the geosphere) then a 3D model of the GBI may be required to map that input flux to a spatially distributed output flux. This might be appropriate if it was considered that most of the dispersion and dilution of the radionuclide plume occurred within the GBI.

Within the framework of the adopted dimensionality, the various components of the model need to be identified. These can be spatially distinct, e.g. topsoil and subsoil, or spatially co-extensive, e.g. rock matrix solids and pore water within the rock matrix. It is these components that provide the context for determining the importance of various processes within the GBI.

Step 7: Process Identification and Importance Specification

From application of the methodology described above, a 3D descriptive model of the GBI would be obtained, together with an evaluation as to how that 3D model should be represented geometrically (i.e. in terms of dimensionality) when implemented in a mathematical model. Furthermore, the key characteristics of the components of that model (e.g. porosity of the rock, chemical composition of pore and fracture waters, temperature of the rock) would have been identified. On the basis of this 3D descriptive model and its geometric representation, it will be appropriate to move on to identify the processes relating those characteristics that need to be included in the model (Step 7a). In identifying the processes, it is helpful to characterise them under the following headings:

- hydrological and hydrogeological;
- geochemical;
- thermal;
- mechanical (e.g. erosion and deposition; freezing-induced stresses);
- biotic (microbiological, macrofloral and macrofaunal);
- nutrient and/or energy based.

Some indication of the types of processes of relevance will already have been obtained at the sub-system description step. However, that analysis will have been undertaken at a general descriptive level. At this later step in the methodology, the system is more precisely defined both geometrically and in terms of the spatial domains occupied by the individual components. Thus, process identification and importance evaluation can be undertaken more precisely.

In addition, if a changing GBI is being represented, it will be appropriate to take into account both natural events and human-induced perturbations.

It is emphasised that the identified processes are taken to be relevant across the whole GBI domain, though their significance will vary between different parts of that domain (for example freezing and thawing will be important in the active layer of a permafrost regime, but will not be of importance at greater depths where the sediments remain permanently frozen). Thus, process identification leads to a list of processes that have to be assessed for significance to components of the domain. For example, bioturbation may be assessed as having a high significance in topsoil, a moderate significance in subsoil, and low significance in unconsolidated Quaternary deposits underlying the subsoil. Thus, process identification results in a list of processes of relevance for inclusion in the mathematical model, together with an evaluation of their significance in the various components of the geosphere-biosphere sub-model domain.

Having identified the processes and their significance, consideration can be given to their degree of coupling (Step 7b). The first stage is to develop an interaction matrix with the components of the GBI as diagonal elements and the processes of relevance as off-diagonal elements. An illustration for a fractured hard-rock aquifer is shown in Figure B.5.

Note that the interaction matrix does not aim to illustrate all the processes that relate these components of the GBI. Rather, it is specifically targeted at those processes that influence radionuclide transport. Alternative matrices could be drawn up to represent other aspects of the system, e.g. heat transport. Also, the matrix can combine elements that are spatially distinct with elements that are spatially co-extensive.

In broad terms, the degree of coupling between different components of the system may be considered to range from weak to strong. The strength of the coupling, the timescale over which it operates and its directionality (i.e. whether it operates only from component A to component B or whether it also operates from component B to component A, described as unidirectional and bidirectional, respectively) determine how it should be represented in mathematical modelling. Alternative approaches are for models of the relevant processes to be uncoupled, loosely coupled or tightly coupled.

4. ILLUSTRATIVE EXAMPLE OF APPLICATION OF THE METHODOLOGY

To illustrate how the methodology described in Section 3 is applied, several examples are explored in Appendix B. One of these, applicable to Lowland Britain, is summarised here. The assessment context within which this example is developed is summarised in Table 4.1.

Table 4.1: Summary of the Assessment Context

Aspect of the Assessment Context	Summary of the Characteristics of this Aspect of the Assessment Context
Purpose of the assessment	Generic assessment intended to demonstrate that a geological disposal facility can be constructed and achieve satisfactory post-closure performance in a range of different geological contexts.
Endpoints of the assessment	Primarily radiological impacts on an individual representative of those more highly exposed in the population {the representative member of a Potential Exposure Group (PEG)}. However, the radionuclide concentrations in environmental media calculated for this purpose may also be used for assessing radiological impacts on non-human biota.
Assessment philosophy	Cautiously realistic, i.e. where there are significant uncertainties cautious assumptions are made, but an attempt is made to avoid the excessive caution that arises from combining several different sets of cautious assumptions, i.e. the overall assessment should be a cautious, but realistic evaluation of how the system is expected to perform.
Repository system	Geological disposal facility at some hundreds of metres depth accommodating both intermediate-level and high-level waste, but with the panels in which the waste types are disposed separated from each other by some distance.
Site context	An inland site in Lowland Britain with the host rock comprising either hard rock or softer sedimentary rock. Evaporites are not available in this context, so are not included in the assessment.
Source term	Spatially distributed plume of radionuclides entering Quaternary sediments from the underlying weathered host rock.
Time frames for assessment	Quantitative assessment required out to 1 10^6 years after closure, but with a greater emphasis on complementary considerations after about 1 10^5 years. Here attention is focused on the first 2 10^5 years after closure, for which detailed landform projections have been made.
Societal assumptions	Technology and societal characteristics are similar to those of the present day, but the society is adapted to the prevailing climate conditions by reference to analogous locations and communities existing at the present day.

4.1 STAGE 1: IDENTIFICATION AND JUSTIFICATION OF GEOSPHERE-BIOSPHERE SUB-SYSTEMS FOR LOWLAND BRITAIN

4.1.1 Step 1: Identification and Justification of Components of the Geosphere-biosphere Sub-system

The assessment context does not pre-define the GBI, nor does it require that sub-system to be time-independent. Furthermore, it indicates that the range of climatic conditions of relevance to be those likely to occur over the next 2 10^5 years. These considerations have to be kept in mind when identifying and justifying the components of the GBI. The relevant components are identified and justified in relation to the specific assessment context in Table 4.2.

Table 4.2: Geosphere-biosphere Sub-system Components for Lowland Britain

Geosphere-biosphere Sub-system Component	Component Description in the Assessment Context	Justification
Climate and atmosphere	The climate will range from temperate at the present day to sub-tropical in the next few hundred years, but with longer term cooling. This could result in sub-arctic to temperate conditions at the end of the 2 10^5 year period, but, in the extreme, could result in a glacial episode at 1 10^5 years recovering to temperate conditions at about 1.1 10^5 years and a subsequent slow cooling. There is a limited marine influence on atmospheric characteristics.	Long-term climate modelling conducted within BIOCLIM [2004].
Geographical extent	Local area of a few square kilometres to a few tens of square kilometres where the radionuclide plume emerges into the Quaternary sediments.	Based on the spatial extent of the proposed geological disposal facility and the likely degree of dispersion of the plume in the overlying rock.
Location	Inland site in Lowland Britain.	Defined in the assessment context.
Topography	Undulating lowland, where lines of low hills are separated by broad open valleys and where 'islands' of upland break the monotony of the more level areas.	See description of Lowland Britain given in Appendix B.
Human community	Small rural communities making maximum reasonable use of local foods are most relevant for defining PEGs.	From consideration of endpoints of the assessment in the assessment context.
Near-surface lithostratigraphy	Quaternary sediments of complex geometry comprising layers and lenses that will often have been disturbed by post-depositional processes.	Examination of Quaternary maps of Britain [British Geological Survey, 1977a].
Water bodies	Surface water bodies are mainly flowing rivers and streams. Substantial lakes and wetlands are uncommon, but do occur. Perched aquifers may be present in the Quaternary deposits. The regional water table may either be located within the underlying bedrock or within the Quaternary deposits. In some contexts, the Quaternary deposits may act to confine a regional aquifer exhibiting artesian conditions.	Based on the description of Lowland Britain given in Appendix B. See also British Geological Survey [1977b].
Biota	Intensively farmed environment. Cereal crops, root crops and green vegetables are grown. Fruit growing is practiced extensively, with different areas specialising in soft fruits and tree fruits. In the lower areas, arable land extends over the ridges, as well as occurring in valley bottoms. Grasslands are more common on the higher ridges of the chalk downlands, but, even there, arable agricultural activities can be observed. Sheep grazing is characteristic of these higher areas, but the rearing of cattle for milk and meat is more characteristic of the lowland pastures. Small herds of goats are kept. However, most goats are kept in small numbers domestically. Pigs are reared commercially and domestic fowl are reared both commercially and domestically.	Based on the description of Lowland Britain given in Appendix B.

4.1.2 Step 2: Consideration of Environmental Change

Step 2 in the methodology requires determination of whether environmental change needs to be taken into account in defining the GBI. If so, then global and regional changes have to be propagated to the local level. From the assessment context, it is determined that the range of climatic and landscape characteristics applicable over the next 2 10^5 years are to be taken into account, with human societal characteristics being as they are at the present day, but adapted to the climate conditions by reference to present-day societal characteristics at analogue locations.

The global and regional changes to be addressed are shown in Figure B.2. Volcanism is not an issue in a UK context. Also, orogeny, large meteorite impacts and large seismic events are extremely unlikely to occur in a British context within the next 2 10^5 years. Therefore, for the purposes of this illustrative analysis, attention is focused on global climate change, as influenced by human and natural factors, the effects of such global climate change on continental ice sheets and global sea level and hence on the regional EFEPs shown in Figure B.2.

This requires first that the regional response should be described and that it should then be propagated down to the local level. In the context of this illustrative example, which relates to a generic assessment for an inland site in Lowland Britain, the distinction between regional and local changes is less distinct than would be the case for a site-specific assessment.

The regional response is determined by studies outwith those specific to the GBI. These may involve the use of global climate models coupled to models of ice-sheet development, global sea-level and isostatic response to both ice and water loading. Alternatively, the regional response may be based on palaeoenvironmental indicator data, e.g. relating to the last glacial-interglacial cycle (MIS 5e through to the present day). For the purpose of this illustrative study, the assessment of regional conditions is based on the modelling studies reported in BIOCLIM [2004]. Results of this process for Central England are summarised below. More detail is given in Appendix B.

Regional Climate Regime

BIOCLIM [2004] concluded that overall, for scenarios involving a significant anthropogenic contribution to greenhouse-gas-induced warming, it seems reasonable to assume that, over the next few hundred years, mean annual temperatures in Lowland Britain will increase from about 10°C to between 13°C and 16°C. The seasonal variation in temperature (warmest month – coldest month) may remain as it is at the present day (~ 12°C) or may weaken slightly (to ~ 9°C). Winter precipitation could be only marginally higher than it is at the present day, or increase by as much as 1 to 2 mm d^{-1}. In contrast, precipitation in summer is likely to decrease by 0.2 to 1.4 mm d^{-1}.

BIOCLIM [2004] also concluded that following a peak in mean annual temperature over the next few hundred years, a cooling trend will ensue, such that temperate conditions similar to those of the present day will recur at between 60 ka and 160 ka AP in the scenarios involving a significant anthropogenic contribution to greenhouse-gas-induced warming. Thereafter, there is no strong trend in climate through to 200 ka AP, though there could be a brief cold episode in the range of EC to EO conditions at around 175 ka AP, with those conditions persisting for a few thousand years.

The main climatic change associated with the return to temperate conditions at between 60 ka and 160 ka AP, is a general cooling throughout the year of between 3 and 6°, with any changes in seasonality being very limited. Winter precipitation may decrease somewhat and summer precipitation is likely to increase, so that the current pattern of precipitation being reasonably uniformly distributed throughout the year is recovered. There may then be further cooling to a ‘boreal’ episode lasting a few thousand years around 175 ka AP. This would be associated with mean annual temperatures ~ 0°C, with a maximum mean monthly temperature of 10 to 18°C in July or August, and a minimum mean monthly temperature of -1 to -20°C in January. The total annual precipitation during this colder episode is expected to be very similar to that at the present day and also relatively uniformly distributed throughout the year. However, modest maxima in mean monthly precipitation either in winter or in summer may occur.

Overall, as BIOCLIM [2004] points out, the period from the present day through to 170 ka AP is characterised by a climate that is only moderately warmer than at the present day and that is associated with a similar degree of water availability throughout the year, though with somewhat drier summers. As BIOCLIM [2004] comments, the main factor in landscape evolution over this period is not climate change relative to the present day, but the duration of the period of interglacial conditions that is projected to occur. A period of interglacial conditions lasting 180 ka (from the beginning of the Holocene at around 10 ka BP to 170 ka AP) is unprecedented for Central England during the Quaternary. However, because some parts of the area of interest were beyond the margins of the British ice sheet at the Last Glacial Maximum (MIS 2 at around 18 ka BP) and have not been glaciated since the peak of the Anglian glaciation (attributed to MIS 12 at around 440 ka BP), information exists relevant to long-term rates of generalised denudation and incision of such a landscape (see below).

BIOCLIM [2004] also investigated a scenario in which there was not a significant degree of global warming associated with anthropogenic greenhouse-gas emissions. Although such a scenario is highly improbable, it does provide a useful illustration of the future pattern of climate that might occur if the climate system is much less sensitive to greenhouse-gas emissions than is currently postulated. In this scenario, temperate conditions similar to those at the present day persist for the next 50 ka. At that time, a cooling transition to Köppen-Trewartha class EO conditions is projected to occur. These conditions are projected to persist until around 100 ka AP. At that time, a rapid cooling through class EC to full glacial conditions (class FT) is projected to occur. Those glacial conditions are estimated to last for only a few thousand years before amelioration in climate occurs, recovering to temperate conditions by about 120 ka AP. Thereafter, a general cooling trend ensues, with class EO conditions from about 140 to 155 ka AP, a brief amelioration to temperate conditions to 160 ka AP, then a cooling through EO to EC conditions at 200 ka AP.

Regional Ice-sheets and Glaciers

The British Isles are unglaciated at the present-day. Based on the BIOCLIM [2004] climatic studies for scenarios involving a significant anthropogenic contribution to greenhouse-gas-induced warming, conditions would never be colder than ‘boreal’ at around 175 ka AP. Therefore, there is no reason to include regional ice-sheets or glaciers in the description of the environment applicable out to 200 ka AP. Even in the scenario in which there was not a significant degree of global warming associated with anthropogenic greenhouse-gas emissions, full glacial conditions were only projected to occur for a few thousand years at around 100 ka AP. During such an episode, it is likely that corrie glaciers would form in upland areas such as Western Scotland and Cumbria, and ice caps might even develop in these areas. However, the duration of the episode would be too short for those ice caps to grow into extensive ice sheets. Therefore, the degree of ice-loading of the crust would be very limited and there would be no advance of ice over lowland areas.

Regional Isostacy

From the discussion of regional ice sheets provided above, it is clear that isostatic depression of Lowland Britain will not be a major factor influencing landform development over the next 200 ka. Furthermore, little residual uplift remains to be expressed from the ice loading that occurred at the time of the Last Glaciation. Indeed, relative sea-levels have been approximately constant around the British coastline for approximately the last 6 ka, i.e. throughout the Late Holocene global sea level highstand [Shennan *et al.*, 2006].

Regional Landform and Sea-level

As noted above, in the scenario characterised by significant anthropogenically induced greenhouse-gas warming, the period from the present day through to 170 ka AP is characterised by a climate that is only moderately warmer than at the present day and that is associated with a similar degree of water availability throughout the year, though with somewhat drier summers. Over this period, the main factor in landscape evolution is not climate change relative to the present day, but the duration of the period of interglacial conditions that is projected to occur.

However, as noted above, some parts of the area of interest have not been glaciated since the peak of the Anglian glaciation at around 440 ka BP, so information exists relevant to long-term rates of generalised denudation and incision of such a landscape, provided that due account is taken of the colder conditions that persisted through much of the period.

Based on this information, it has been determined the additional incision of stream channels that might be expected to occur over the next 170 ka can be bounded by use of data relating to the Anglian till. In that case, the maximum depth of incision that has occurred is 60 m over 440 ka. It seems likely that about 40 m of this probably occurred within 20 ka of deposition of the till. Thus, if a maximum of 20 m of incision has occurred over the last 420 ka, the additional incision over the next 170 ka should be no more than about 8 m. It could be substantially less if streams have already achieved a close to equilibrium profile. Also, it should be kept in mind that over the last 420 ka the sea level was typically some tens of metres lower than at the present day, so the main rivers would have been graded to a lower base level throughout much of the period. On interfluves, the overall depth of denudation over the next 170 ka is unlikely to exceed 1 m, as no intervals of arid conditions are postulated that could substantially enhance Aeolian erosion. Overall, the average depth of erosion over the next 170 ka is estimated to be 1.7 m. With up to 8 m of additional incision over the next 170 ka and 1.7 m on average, slope angles should not increase by more than about 10%. Thus, topographic changes are assessed as very limited.

In principle, one factor that could affect the above analysis is a change in sea level, as this is the ultimate determinant of base level. However, in the scenarios with anthropogenic greenhouse-gas warming addressed in BIOCLIM [2004], there is generally a smaller global ice volume throughout the next 170 ka than at the present day. Thus, sea level will be at, or a few metres above, its present level throughout the period.

Outside the river valleys, the degree of surface lowering over the period is expected to be less than 1 m. Therefore, there will be very little increase in the area of land from which till is completely removed exposing the underlying parent material. Generalised Aeolian and fluvial erosion will remove existing superficial soil horizons. However, the soil system will remain covered with vegetation, so a new organic A horizon will continually be formed and changes in the soil profile are expected to be very limited. In the river valleys, several metres of erosion could result in removal of the till in some areas and the establishment of new hydraulic connections between surface waters and the underlying rock. It seems unlikely that the nature and extent of alluvial deposits would be substantially altered. However, the spatial pattern of those deposits might alter somewhat, with switching between erosional and depositional regimes being determined by detailed spatial and temporal changes in the flows of surface waters.

Losses of material by solubilisation (chemical erosion) are likely to be very limited compared with fluvial and Aeolian erosion, except, possibly, in the case of the outcrop of the Chalk east of The Fens. However, the low elevation of this Chalk outcrop is regarded as mainly due to the effects of the Anglian ice, so it seems unlikely that chemical erosion would result in lowering of that outcrop by more than a few metres over the next 170 ka.

Regional Land Use, Vegetation and Soils

Only limited changes would be expected in the types of soil profile present. Therefore, the main controls on vegetation and land use would be climatic.

As discussed in BIOCLIM [2004], under the warmer climate conditions expected to occur in the scenarios with significant anthropogenically induced greenhouse-gas warming and with irrigation, a wide range of crops could be grown, as at the present day. Furthermore, there is also no reason why animal husbandry practices should be very different from those of the present day, except that pasture might be irrigated and animals would be able to graze such irrigated pasture throughout the year. As the climate cooled, patterns of agriculture would not be expected to change markedly, but there would be some reduction in the demand for irrigation. Also, there is good reason to consider that the landscape would continue to be fully utilised for human activities throughout the warming and cooling phases considered herein, i.e. no increase in the extent of natural and semi-natural biotic communities needs to be taken into account.

Beyond 170 ka AP and under EO or EC conditions, a largely treeless landscape is likely to develop, either from forested or unforested antecedent conditions (this also applies to the FT state projected to arise in the scenario without significant anthropogenically induced greenhouse-gas warming at around 100 ka AP). Agriculture would be largely animal husbandry, with land given over to grass for either summer grazing or hay production. Animals would be over-wintered indoors. Arable cultivation would mainly be of vegetables, with barley grown in areas with the least severe climate. Extensive areas of natural vegetation are likely to develop, i.e. the spatial extent of utilisation of the landscape by humans is likely to decrease. This natural vegetation would comprise mainly various types of low-growing shrubs (tending to tundra-type vegetation in EC conditions). With a low productivity agricultural system based on livestock husbandry, small villages, hamlets and isolated homesteads widely dispersed over the rural landscape are likely to be the characteristic human communities. However, it would be possible to sustain a mix of urban and rural communities as at the present day.

Regional Hydrology, Hydrogeology and Hydrogeochemistry

With the limited changes in topography projected over the next 170 ka and the limited changes in either amounts of precipitation or seasonal temperatures, it seems unlikely that there would be substantial changes in the pattern of surface water flows or in groundwater levels. Thus, the overall surface and near-surface hydrological system is likely to be very similar to that at the present day. These remarks reflect the maturity of the landscape. However, it is noted that substantial changes in hydrology could occur as a consequence of human activities. At an inland site, the groundwaters present in the Quaternary deposits are likely to exhibit a chemical composition characteristic of recent meteoric water.

Beyond, 170 ka AP, the EC climate that could occur is typically characterised by warmer summers than EO and much colder winters. Overall, this results in a mean annual average temperature about 5°C colder. It is debatable whether this extreme contrast in continentality would apply in Lowland Britain, though it might arise as a result of changes to ocean circulation patterns in the northeast Atlantic. If an EC climate were to occur, substantial changes to water bodies would be expected. Very cold winters would lead to extensive snowpack development and the freezing of rivers. The spring melt would be associated with ice dams in the rivers and very high peak flows. In consequence, there would be considerable remodelling of river channels. Similar effects would be expected under the FT conditions postulated to occur in the scenario without significant anthropogenically induced greenhouse-gas warming.

Discontinuous permafrost would be present, overlain by a seasonal active layer. Soil structures, such as ice wedges, that are characteristic of cold regions would be expected to form.

Regional Atmosphere

No substantial changes in the regional atmosphere are projected to occur.

Propagation of the Regional Changes to a Local Level

It is first relevant to note that under both of the scenarios with and without significant anthropogenically enhanced greenhouse warming, sites in Lowland Britain are likely to be well beyond the margins of any ice caps that are present. Therefore, for illustrative purposes, it is sufficient to consider a site subject to anthropogenically enhanced greenhouse warming leading to a period of sub-tropical to temperate conditions out to 170 ka AP. Thereafter, cooling through EO to EC/FT conditions can be assumed.

The site can be assumed to be located within the boundaries of a surface-water catchment or sub-catchment with an area of a few tens of square kilometres (i.e. large enough to receive the radionuclide plume arising from the geological disposal facility). Over the 200 ka period being considered, the interfluves bounding that catchment will be lowered by less than 1 m and the stream and river channels present within it will deepen by up to 8 m, but generally by rather less than this.

The lithostratigraphy of the catchment comprises a mixed sequence of unconsolidated Quaternary deposits overlying weathered bedrock. Deeper groundwaters discharge from the weathered bedrock over at least part of the catchment area and they mix with recent meteoric waters within the Quaternary sediments. The deeper groundwaters may be confined in some areas and artesian conditions can develop. Stream and river channels are mainly developed in the Quaternary deposits, but can be incised through to the weathered bedrock at some locations, and the extent of such incision may increase with time due to the deepening of the stream and river channels. The stream and river channels may include both discharging and recharging sections along their lengths, with the extent of the discharge and recharge sections varying seasonally and altering as the climate changes.

Over the first 170 ka of the assessment period, the entire area of the surface-water catchment can be taken to be utilised for intensive agriculture (both arable and animal husbandry), but with a local community present that also undertakes garden cultivation of fruit and vegetables, and rears various types of animals, including hens, goats and pigs. The main changes over this period will be in relation to irrigation requirements that will be determined by the types of crops being grown and the current climate. Soil characteristics will not alter substantially over this period.

Beyond 170 ka AP, the cooling climate will result in a gradual reduction in the extent of agriculture. The catchment will become increasingly dominated by a low shrub, semi-natural vegetation with the eventual outcome being tundra-type vegetation. In the earlier part of the period, seasonal freezing of the superficial soil layers will occur and gelic histosols will begin to develop. In the latter part of the period, discontinuous permafrost will begin to develop and will eventually penetrate through the full depth of the Quaternary deposits. It will be overlain by a seasonally active layer not more than about one metre deep. Also in the latter part of the period, very cold winters will lead to extensive snowpack development and the freezing of rivers. The spring melt will be associated with ice dams in the rivers and very high peak flows. In consequence, there will be considerable remodelling of river channels, but the overall depth of incision will not exceed 8 m.

4.1.3 Step 3: Examination of Narratives of Environmental Change

In the example described here, it has been possible to condense all the environmental changes of relevance identified in scenarios with and without significant anthropogenically induced greenhouse-gas warming into a single narrative, as provided in Section 4.1.2. The one omission from this narrative is an account of the transition from an EC/FT climate to an interglacial (DO) climate. However, this could be addressed by extending the narrative out somewhat beyond 200 ka AP. Thus, a conclusion from this analysis is that, in this case, the safety assessment can proceed on the basis of a single narrative.

In broad terms, the narrative set out above corresponds to a sub-system with a time-independent geometry over the first 170 ka, but with water flows that change with time according to the prevailing climate. However, there is one exception to this, in that a significant degree of stream incision may occur over the period. Therefore, setting aside the initial warming transition (which takes place over a few hundred years), it seems useful to distinguish the first 170 ka into two states (S1 and S2) with an extended transition (T1) between them. The two states are briefly summarised in Table 4.3, using the standard set of GBI components.

Table 4.3: States of the Geosphere-biosphere Sub-system that are taken to be Applicable over the First 170 ka

Component	Description for S1	Description for S2
Climate	Mean annual temperature 13°C and 16°C (3°C to 6°C warmer than at the present day). The seasonal variation in temperature (warmest month – coldest month) may remain as it is at the present day (~ 12°C) or may weaken slightly (to ~ 9°C). Winter precipitation could be only marginally higher than it is at the present day, or increase by as much as 1 to 2 mm d^{-1}. In contrast, precipitation in summer is likely to decrease by 0.2 to 1.4 mm d^{-1}.	DO climate, as obtained from climate stations in Lowland Britain at the present day.
Atmosphere	As at the present day.	As at the present day.
Topography	As at the present day.	As at the present day, except that stream and river channels are incised by up to 8 m. Incision of minor streams should be only a small fraction of 8 m, whereas incision of the main river channel should grade to a maximum of about 8 m at its outlet from the catchment.
Near-surface lithostratigraphy	As at the present day.	As at the present day except for the effects of incision. Sediments removed by incision are assumed to be lost from the catchment in suspension in flowing surface waters.
Water bodies	Surface water flows and groundwater recharge rates adapted from present day values to allow for the effects of the warmer climate on effective precipitation. Presence and extent of perched water bodies adjusted accordingly.	Surface water and groundwater flows and the distribution of perched water bodies identical to those at the present day.
Biota	Intensive agriculture and garden cultivation, as at the present day.	Intensive agriculture and garden cultivation, as at the present day.

The extended transition T1 from S1 to S2 is defined in terms of three major factors:

- A cooling of climate;
- An extended period of incision with the eroded sediments being lost from the catchment in river flow;
- An adaptation of the surface-water and groundwater flow systems to the changing climate and altered hydraulic connectivity resulting from the incision.

Beyond 170 ka AP, the cooling that occurs within the remainder of the 200 ka period for which the narrative is defined is distinguished into two further states (S3 and S4) and two further transitions (T2 and T3). Details of these states and transitions are given in Appendix B.

The periods of the states and transitions are not defined in the above, nor need they be at this conceptual stage. However, for guidance, the periods shown in Table 4.4 are considered to be realistic. These allow a long period for incision to occur and also provide an extended period (15 ka) for permafrost to develop to depth.

Table 4.4: Illustrative Durations for the States and Transitions of Interest.

State or Transition	Period (ka AP)	Duration (ka)
S1	0-40	40
T1	40-130	90
S2	130-170	40
T2	170-175	5
S3	175-180	5
T3	180-195	15
S4	195-200	5

4.2 STAGE 2: DESCRIPTION OF GEOSPHERE-BIOSPHERE INTERFACE

Having identified the four states S1, S2, S3 and S4, the next step is to develop interaction matrices showing the processes operating between the individual components of the GBI for each of those states (Step 4). The interaction matrix for state S1 is shown in Figure B.19. In the remainder of this section, State S1 is used to illustrate the application of the later steps in the methodology.

In Figure B.19, the shaded cells indicate interactions that are likely to be of significance. These cells form clusters that are relevant for the later analysis. This is illustrated in the influence diagram shown in Figure 4.1.

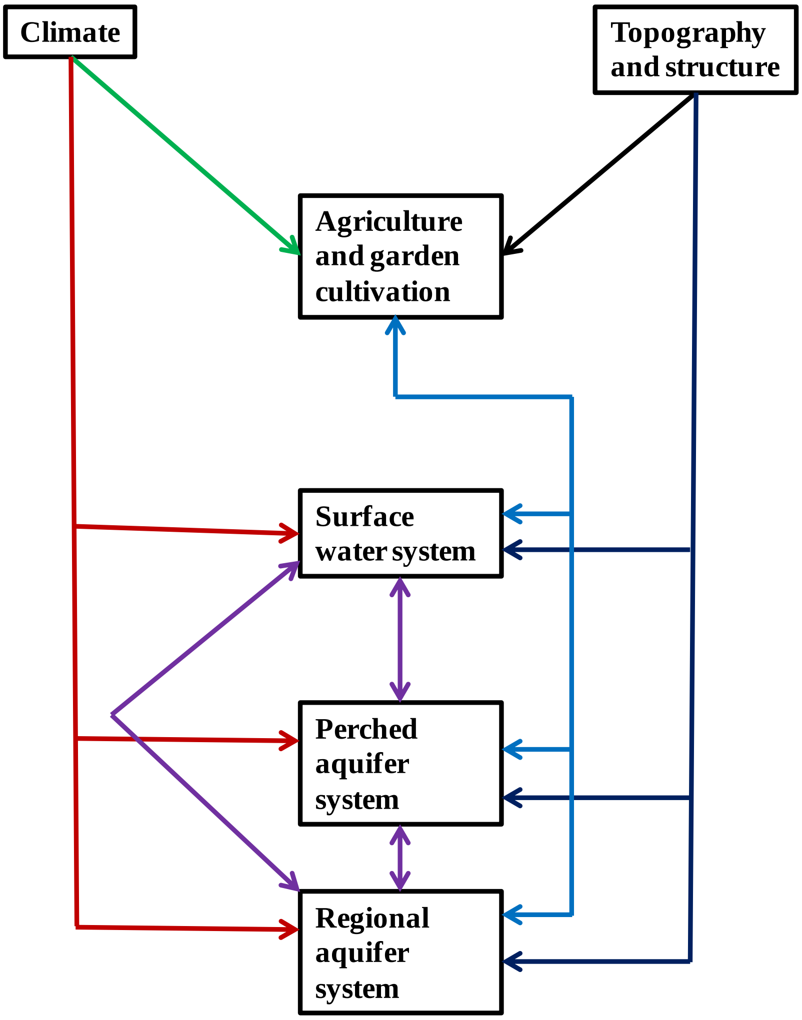


Figure 4.1: Simplified Influence Diagram abstracted from the Interaction Matrix shown in Figure B.19.

Topography and structure (lithostratigraphy) are closely related to each other and are conveniently considered together. In this time-independent state in which no incision or sedimentation is occurring, the topography and structure can be defined independent of the other components of the GBI. Similarly, the local subdued topography and hydrological system have only very minor influences on the local climate, so the climate can be defined independent of the other components of the GBI.

Agriculture and garden cultivation are strongly influenced by both climate and topography, but they do not have a significant influence on those factors. In contrast, agriculture and garden cultivation strongly influence and are influenced by all components of the hydrological and hydrogeological system (largely through water abstraction). Climate also strongly affects all aspects of the hydrological and hydrogeological system, since it is the primary control on the amounts of water available. In addition, all aspects of the hydrological and hydrogeological system are closely coupled to each other.

4.3 STAGE 3: CHARACTERISATION OF THE GEOSPHERE-BIOSPHERE INTERFACE

This step applies to each state of the GBI. Here this analysis is performed for State S1 only. Additional material on States S2 to S4 is given in Appendix B. This step requires consideration not only of the components of the sub-system (which have largely already been identified), but also their geometry, their spatially distributed properties and the processes that operate within and between them. Because of this emphasis on geometry, except for the local climate, the characterisation is most conveniently performed in terms of a sequence of 3D visualisations showing the various aspects of the GBI (Step 5 with Step 6 included through the development of 3D visualisations).

4.3.1 Climate

The climate of Lowland Britain under greenhouse-warmed conditions (Cr (subtropical rain) or Cs (subtropical winter rain) in the Köppen-Trewartha classification) is fully characterised in Appendix C of BIOCLIM [2004]. Under Cr conditions, the mean temperature of the coldest month is between about 5ºC and 10ºC, whereas the temperature of the warmest month is between 18ºC and 22ºC. Under Cs conditions, the mean temperature of the coldest month is between 6ºC and 14ºC, whereas the mean temperature of the warmest month is between 22ºC and 27ºC. The mean annual temperature over the analogue stations considered is slightly below 15ºC for Cr and about 17ºC for Cs. However, the Cr and Cs stations individually comprise a continuum with mean annual temperatures ranging from 10ºC to 20ºC. Thus, they encompass a sufficient range to represent the long period of cooling back down to current temperate (DO) conditions.

Precipitation in Cr conditions peaks in the winter months at about 100 to 140 mm per month and is at a minimum in July and August at about 20 to 50 mm per month. Under Cs conditions, precipitation peaks in the winter months at 50 to 200 mm per month and is low (0 to about 50 mm per month) from May to August. Averaged over all the analogue stations considered, the maximum precipitation in winter is about 120 mm per month in Cr conditions and about 100 mm per month in Cs conditions. Similarly, the minimum precipitation in summer is about 30 mm per month in Cr conditions and about 10 mm per month in Cs conditions. The annual mean precipitation in Cr conditions is approximately 1000 mm, which can be compared with about 650 mm in Cs conditions and about 630 mm in temperate (DO) conditions.

Under Cr conditions, there is very little difference between the analogue stations in terms of moisture excess or deficit (defined as precipitation minus potential evapotranspiration). In December and January the moisture excess is around 100 mm per month, dropping to zero in May. In June, July and August, there is a moisture deficit in the range 50 to 120 mm per month, but in September the moisture deficit is around zero and the moisture excess then increases during October and November back to its peak value in December. Under Cs conditions, the moisture excess in the winter months is typically 30 to 150 mm per month, but the excess falls to zero in April and does not rise above zero until October. From May to September, there is a moisture deficit that reaches approximately 150 mm per month in July.

In terms of overall annual moisture excess or deficit, there is a strong distinction between Cr and Cs conditions. In typical Cr conditions, there is an annual moisture excess of over 200 mm (compared with a near-zero excess in temperate, DO conditions). In contrast, in typical Cs conditions, there is an annual moisture deficit of around 200 mm. Thus, Cr conditions are generally rather wetter than those prevalent today, whereas Cs conditions are significantly drier, tending towards a semi-arid environment. In contrast to temperature, there is a strong distinction in precipitation between the Cr and Cs analogue stations, rather than a continuum of characteristics.

This annual distinction is also reflected in the summer (May to August) moisture deficit. This is about 240 mm in Cr conditions (compared with about 180 mm in temperate, DO, conditions), but is much larger, at about 450 mm, in Cs conditions. Thus, whereas irrigation of crops may only be required in some years in DO and Cr conditions, it would be required in almost all years in Cs conditions, and irrigation of pasture (or fodder crops) may also be undertaken. (See also Figure 3.3 in BIOCLIM [2004], which displays the contrast between annual summer soil moisture deficits at Bordeaux (Cr) and Perpignan (Cs) over the period 1950 to 1990).

4.3.2 Topography and Lithostratigraphy

The topography at the present day is that of the Anglian till, as illustrated in Figure B.21.

Any one of the valley systems shown on Figure B.21 could be adopted as the surface-water sub-catchment into which the discharge of contaminated groundwater is projected to occur. However, for convenience, a simple V-shaped catchment might be used for illustrative purposes, with only minor channels draining into the central river valley.

The lithostratigraphy of the Anglian till is taken from the Quaternary geology map of Southern Britain [British Geological Survey, 1977a]. The relevant area is illustrated in Figure B.22.

The upland areas are described as Boulder clay and Morainic Drift. Along the river valleys are deposits of sand and gravel of uncertain age or origin and limited areas of alluvium. The Boulder Clay and Morainic Drift is described as representing mainly ground moraine, the distinction between Boulder Clay and Morainic Drift being in places largely topographic. The definition also encompasses undifferentiated glacial drift. The deposits of sand and gravel are largely river terraces standing above the present flood plain. Most of these terraces are mainly sand and gravel, but some comprise, or are capped by, silt and clay. The underlying chalk outcrops to the northwest of the area illustrated in Figure B.22.

If a single river valley is adopted as being the sub-catchment of interest, the main Quaternary deposit should be taken to comprise boulder clay, incorporating lenses of sand, gravel or loam. Within the river channel, a terrace or terraces of sand and gravel can be included superimposed on the underlying Boulder Clay. The underlying bedrock of the region comprises mainly Neogene deposits of gravel, sand, silt and clay, but there are also areas of chalk formed during the Cretaceous. It seems reasonable to assume discharge from a chalk aquifer underlying the Boulder Clay. Based on the above analysis, an illustrative sketch of the type of catchment of interest is provided as Figure 4.2.

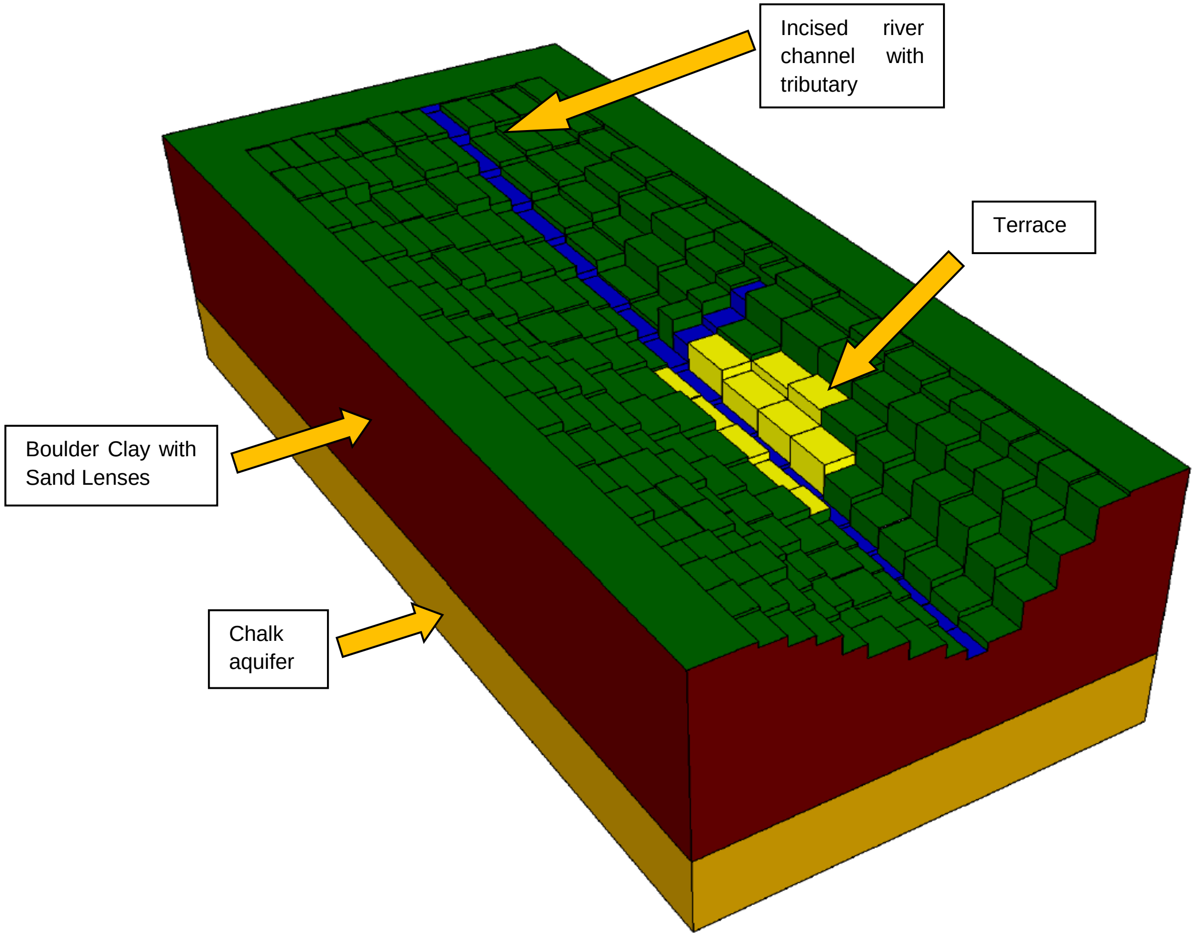


Figure 4.2: Illustrative Catchment of Interest (also showing how it might be discretised in a simple finite-element model).

A typical cross-section across such a catchment is as illustrated in Figure 4.3.

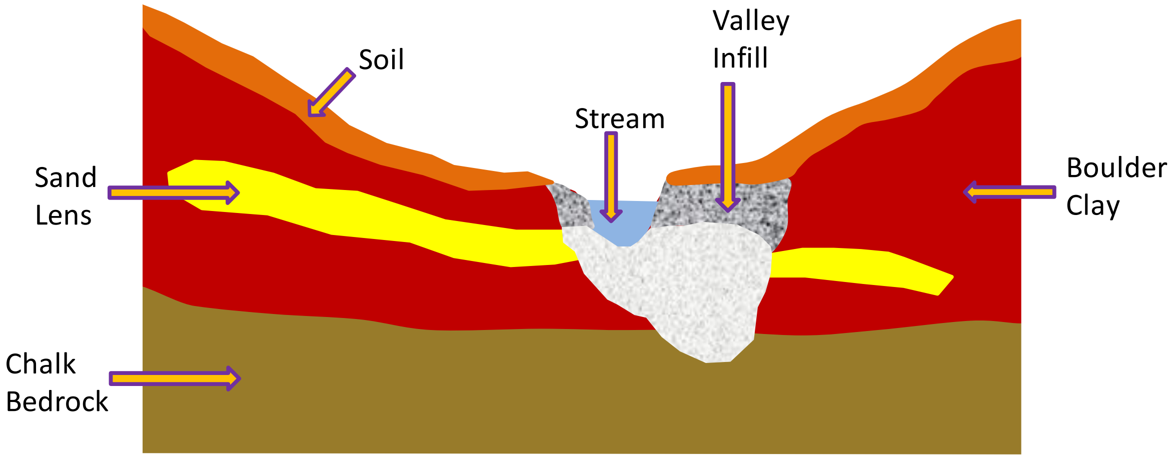


Figure 4.3: Typical Cross Section of the Catchment of Interest.

4.3.3 Surface Water and Groundwater Flow Regime

Meteoric water will mainly penetrate the soil, but will tend to be deflected sub-horizontally at the interface with the boulder clay and will be transferred downslope to the stream channel or the valley infill. A limited amount may percolate through the boulder clay, but be deflected sub-horizontally in any high hydraulic conductivity layers that it encounters. In high intensity rainfall events or after prolonged wet periods, some precipitation may be transferred to the stream channel in surface runoff. The chalk is assumed to host an aquifer that is confined by the overlying boulder clay and is under artesian conditions. This leads to upwelling through the high conductivity valley infill and discharge to the stream and near-stream soils where they are underlain by the valley infill. This discharge region may not be present towards the head of the stream and the upper part of the chalk may be unsaturated in that area. Likely pathways of surface water flow are shown in Figure 4.4. Similar pathways are likely to characterise interflow at the boundary between the overlying soil and the Boulder Clay. Likely pathways of sub-surface flow are shown on a section through the catchment in Figure 4.5.

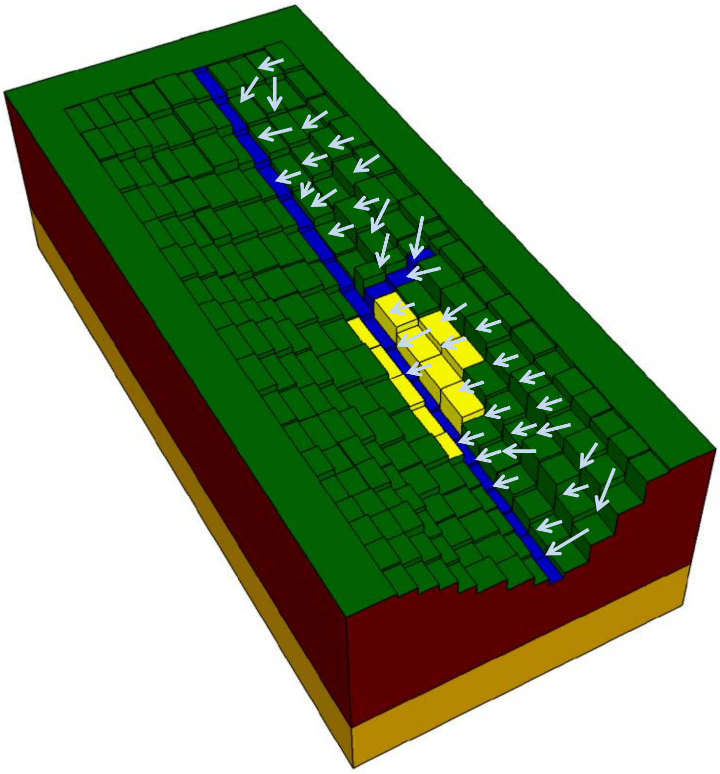


Figure 4.4: Surface Water Flows (shown for one side of the catchment only)

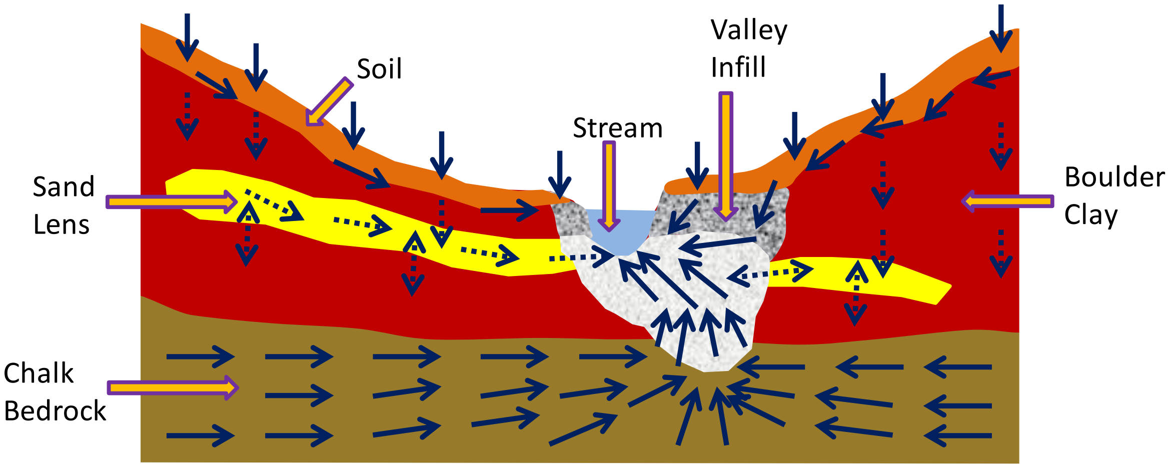


Figure 4.5: Subsurface Water Flows in a Section of the Catchment

In Figure 4.5, the main flows are shown as solid arrows and secondary flows are shown by broken arrows. Surface-water flows are not shown, as these are illustrated in Figure 4.4. Regions where the flow direction is well defined are shown by single-headed arrows and regions where the flow direction is less well defined are shown by double headed arrows. Infiltration is expected to be strongly deflected at the interface between the soil and the boulder clay, leading to a downslope, interflow component. Deeper percolation into the boulder clay is restricted by its low hydraulic conductivity. Some of this deeper percolation is intercepted by the sand lens and is directed downslope. Flow in the chalk bedrock is shown as convergent to the high conductivity valley infill, but it is emphasised that this flow pattern is that relevant to the surface water catchment. Deeper in the chalk, the flow may be unidirectional, governed by the regional topography and lithostratigraphy rather than by local characteristics. The high hydraulic connectivity between the chalk and the valley infill dominates the pattern of up-flow, but because the chalk aquifer is confined, some limited up-flow into the boulder clay would occur, so mixing of aquifer water with recent meteoric water would occur within the boulder clay and sand lens.

4.3.4 Hydrogeochemistry

As illustrated in Figure 4.5, the main water types that will be present comprise recent meteoric water derived from precipitation and upwelling water from the chalk aquifer. The meteoric water will be oxic, but it will become anoxic as it penetrates into the soil and underlying boulder clay. Indeed, it seems likely that the oxygen will be entirely consumed within the soil system. A typical rainfall composition for Eastern England is given in Table B.15.

The water flowing in the chalk aquifer is also likely to be relatively recently derived from meteoric inputs. An illustrative composition is that of the Great Ouse Chalk Aquifer of Eastern England. This Cretaceous chalk aquifer has been identified as the most important aquifer in England [Ander *et al*., 2004]. Its detailed characteristics are given in Table B.16.

This water contains a substantial amount of dissolved oxygen and, consequently, exhibits a positive redox potential. The meteoric water that recharges this aquifer is slightly acidic (pH 5.1), so there is significant dissolution of the chalk resulting in high concentrations of calcium (about 130 mg L^{-1}) and bicarbonate (about 280 mg L^{-1}). As Ander *et al.* [2004] remark, the median value of pH (7.14) and small range are consistent with well-buffered groundwater controlled by carbonate equilibrium. The range of Eh values measured is small and consistently oxidising, with a median value of 423 mV. However, these data show poor quantitative agreement with the DO (dissolved oxygen) data, with which they would be expected to co-vary: this is due to the well-established difficulties in obtaining representative Eh measurements. The DO data show a greater range in the redox conditions than implied by the Eh values. Overall, the Great Ouse Chalk aquifer groundwaters are all of Ca-HCO_3 type, which is typical of unconfined Chalk groundwaters from other baseline studies [Ander *et al*., 2004]. Note that the aquifer in Figure 4.5 is assumed to be confined within the local surface water catchment, but is taken to be unconfined at the larger regional scale and it is this larger scale that defines the local composition.

4.3.5 Thermal Regime

The depth of the section of interest is a few tens of metres. Over this depth range, the geothermal gradient would give rise to a temperature difference of < 1ºC. The main thermal distinction is that the annual temperature cycle at the surface is strongly attenuated within a few metres, such that nearly constant temperatures occur throughout the year at the depth of the regional aquifer.

4.3.6 Perturbations due to Human Actions

In the context of the scenarios of interest, the main perturbation to be addressed is the sinking of a well for use in water abstraction. In State S1, the summer (May to August) moisture deficit is about 240 mm in Cr conditions (compared with about 180 mm in temperate, DO, conditions), but is much larger, at about 450 mm, in Cs conditions. Thus, whereas irrigation of crops may only be required in some years in DO and Cr conditions, it would be required in almost all years in Cs conditions, and irrigation of pasture (or fodder crops) may also be undertaken. Small-scale, garden irrigation may be achieved by wells constructed into perched water bodies present within the boulder clay, but inspection of Figure 4.5 indicates that such water bodies would, in general, be less contaminated than the underlying regional aquifer. Furthermore, the limited sustainability of such perched water bodies could make it more appropriate to extract water from the regional aquifer even in the case of small-scale domestic and garden use. Thus, the appropriate perturbation is a pumped well extending a few metres to several tens of metres into the chalk aquifer and screened through the overlying boulder clay. The pumping rate for this well might be as low as a fraction of a cubic metre per day for a domestic well extending a few metres into the aquifer up to a few hundred cubic metres per day from a well extending several tens of metres into the aquifer with the abstracted water used for commercial agricultural purposes.

4.3.7 Spatial and Temporal Flux of Radionuclides

From Figures 4.4 and 4.5, it is clear that radionuclide fluxes will enter the GBI along the axis of the catchment, primarily through the valley infill. In addition, in State S1, radionuclides may be abstracted from wells drilled into the chalk bedrock with the abstracted fluxes directed to soil or to the central stream of the catchment (if the well is used for river augmentation to compensate for water extracted for various purposes further upstream or downstream). For the purpose of deriving biosphere dose conversion factors (BDCFs) as used by RWMD, it is appropriate to assume constant radionuclide concentrations in the unperturbed part of the chalk bedrock aquifer.

4.3.8 Outputs Required

For determining the applicability and values of BDCFs, it is necessary to estimate time-dependent radionuclide concentrations in soils, well waters and stream waters. The time taken for equilibrium (time-independent) concentrations to be approached in these media can be used to evaluate whether each state would persist for long enough for equilibrium BDCFs to be applicable. The values of the radionuclide concentrations in the various environmental media at or close to equilibrium can be used with supplementary data (e.g. plant:soil concentration ratios, animal product transfer factors, human habits data) to give BDCF values both for humans and for non-human biota.

4.3.9 Processes Operating within the Model and their Significance (Step 7)

Based on the above discussion, the following distinct components of the unperturbed GBI for State S1 are identified.

a) Physical components:
   - a1) Soils
   - a2) Boulder Clay
   - a3) Lenses and other layers of varying lateral extent comprising deposits of significantly higher hydraulic conductivity than the Boulder Clay, e.g. gravel, sand and silt, here described briefly as Sand lenses
   - a4) Valley infill deposits
   - a5) Chalk bedrock

b) Water bodies
   - b1) Stream waters
   - b2) Soil water
   - b3) Groundwater in Boulder Clay
   - b4) Groundwater in Sand lenses
   - b5) Groundwater in Valley infill deposits
   - b6) Chalk aquifer groundwater

c) Water types
   - c1) Meteoric water
   - c2) Aquifer water
   - c3) Mixed water

Water bodies are defined to include both the flow characteristics and composition of those bodies. The composition is determined by the mixing of the various water types together with water-rock interactions with the physical components. Thus, there is a degree of overlap in the definitions of water bodies and water types. However, separating the two allows a natural distinction between aspects that are primarily addressed in hydrogeological studies from those addressed in hydrogeochemical studies.

Processes identified as operating between these components are illustrated in Figure 4.6.

Soils					1,6	1,7	1,8		1,10				1,14
2,1	**Boulder Clay**					2,7	2,8	2,9	2,10	2,11			2,14
		Sand lenses			3,6		3,8	3,9	3,10				3,14
4,1			**Valley infill deposits**		4,6	4,7	4,8	4,9	4,10	4,11			4,14
				Chalk bedrock			5,8		5,10	5,11		5,13	5,14
6,1		6,3	6,4		**Stream waters**	6,7		6,9	6,10				6,14
7,1	7,2		7,4		7,6	**Soil water**	7,8		7,10				7,14
8,1	8,2	8,3	8,4	8,5		8,7	**Groundwater in Boulder Clay**	8,9	8,10	8,11			8,14
	9,2	9,3	9,4		9,6		9,8	**Groundwater in Sand lenses**	9,10				9,14
10,1	10,2	10,3	10,4	10,5	10,6	10,7	10,8	10,9	**Groundwater in Valley infill deposits**	10,11			10,14
	11,2		11,4	11,5			11,8		11,10	**Chalk aquifer**		11,13	11,14
12,1			12,4		12,6	12,7			12,10		**Meteoric water**		12,14
	13,2		13,4	13,5			13,8		13,10	13,11		**Aquifer water**	13,14
14,1	14,2	14,3	14,4	14,5	14,6	14,7	14,8	14,9	14,10	14,11			**Mixed water**

Figure 4.6: Interaction Matrix for Components of the Geosphere-Biosphere Sub-system in State S1.

Some comments on the interaction matrix shown in Figure 4.6 are required. First, the major components of the system are shown on the lead diagonal. Solids are coloured reddish-brown, water bodies blue and the chemical compositions of waters are shown in red. The geometry is that of Figures 4.4 and 4.5, so components that are not in direct contact do not affect each other. Thus, for example, **Groundwater in Boulder Clay** does not directly influence **Stream waters**, as **Valley infill deposits** lies between them. Here and throughout this discussion text in bold refers to the lead diagonal elements in Figure 4.6.

Meteoric water and **Aquifer water** are end members supplied to the GBI from outside. This means that they are not influenced by any components of the GBI, but they can influence components of that sub-system. However, **Meteoric water** and **Aquifer water** are rapidly transformed to **Mixed water** as they penetrate the GBI. Thus, **Meteoric water** only interacts with materials exposed at the surface, i.e. **Soils**, **Valley infill deposits**, **Stream waters**, **Soil water** and **Groundwater in Valley infill deposits** (the **Valley infill deposits** are taken to be exposed at the stream banks). These are interactions 12,1; 12,4; 12,6; 12,7 and 12,10. Note that the interactions can be directly with solids, e.g. solution and precipitation, or with liquids, e.g. mixing. Similarly, **Aquifer water** interacts directly with **Boulder Clay**, **Valley infill deposits**, **Groundwater in Boulder Clay** and **Groundwater in Valley infill deposits** at the interface of the aquifer with these other media (13,2; 13,4; 13,8 and 13,10). **Aquifer water** also interacts with the **Chalk bedrock** and the **Chalk aquifer groundwater** within the aquifer (13,5 and 13,11). Indeed, it is these reactions together with the reverse reactions (5,13 and 11,13) that define the composition of **Aquifer water**, e.g. through precipitation/dissolution reactions in a flowing groundwater system.

A key role of **Meteoric water** and **Aquifer water** is the formation of **Mixed water** (12,14 and 13,14). However, the composition of **Mixed water** is altered throughout the system by direct interactions with solids (1,14; 2,14; 3,14; 4;14 and 5,14) and by interactions with the fluids included in those solids (6,14; 7,14; 8,14; 9,14; 10, 14; 11,14). This implies a complete set of reverse reactions (14,1 through to 14,11). The reactions include sorption/desorption, complexation, solution and dissolution at solid surfaces, and reactions between chemical species in solution. Colloid formation and dissolution are included.

The various solids condition the composition of their included waters (1,7; 2,8; 3,9; 4,10; 5,11) and *vice versa* (7,1; 8,2; 9,3; 10,4; 11,5). Note that **Aquifer water** is an end member and should not be confused with **Groundwater in the aquifer**. The latter is heterogeneous determined both by water mixing and water-rock interactions.

Water characteristics, including composition and flow field are determined by interactions across boundaries. Thus, **Soil water** influences the composition and flow of **Groundwater in Boulder Clay**, by flow across the boundary of the two media (7,8). Also, concentration differences across this boundary can lead to diffusional transport. Flow and transport can also occur in the opposite direction (8,7). Similar interactions across boundaries occur for other components of the sub-system (6,7; 7,6; 6,9; 9,6; 8,9; 9,8; 6,10; 10,6; 7,10; 10,7; 8,10; 10,8; 9,10; 10,9; 8,11; 11,8; 10,11; 11,10).

In addition to solids having an effect on their included waters, they can also affect the composition of waters in adjacent solids. It could be argued that this is mediated by flow and transport in waters across the interface, but it seems appropriate to recognise the complexities of such interfaces by allowing the possibility of a direct interaction (though, in practice, this is likely to be minor). Hence, interactions 1,6; 1,8; 1,10; 2,7; 2,9; 2,10; 2,11; 3,6; 3,8; 3,10; 4,6; 4,7; 4,8; 4,9; 5,8; 5,10 and 4,11 are included together with their reverse interactions of adjacent waters on the solids at the interface (6,1; 8,1; 10,1; 7,2; 9,2; 10,2; 11,2; 6,3; 8,3; 10,3; 6,4; 7,4; 8,4; 9, 4; 8,5; 10,5 and 11,4).

Finally, it is recognised that **Boulder Clay** and **Valley infill deposits** can evolve into **Soils** through the process of pedogenesis (2,1 and 4,1). This is of limited relevance in a time-invariant state, but would need to be addressed in a transition between states that was associated with erosion and incision, since pedogenesis would tend to regenerate the soil profile as superficial material was eroded.

In general terms, interactions at interfaces are likely to be of much less significance than flows across them or interactions within the bulk of the components. (It is of interest to note that this statement would be much more difficult to justify if flow and transport within a sparsely fractured system was under consideration.) This leads to the simplification of Figure 4.6 shown in Figure 4.7, where interactions of minor significance have been greyed out.

Soils					1,6	1,7	1,8		1,10				1,14
2,1	**Boulder Clay**					2,7	2,8	2,9	2,10	2,11			2,14
		Sand lenses			3,6		3,8	3,9	3,10				3,14
4,1			**Valley infill deposits**		4,6	4,7	4,8	4,9	4,10	4,11			4,14
				Chalk bedrock			5,8		5,10	5,11		5,13	5,14
6,1		6,3	6,4		**Stream waters**	6,7		6,9	6,10				6,14
7,1	7,2		7,4		7,6	**Soil water**	7,8		7,10				7,14
8,1	8,2	8,3	8,4	8,5		8,7	**Groundwater in Boulder Clay**	8,9	8,10	8,11			8,14
	9,2	9,3	9,4		9,6		9,8	**Groundwater in Sand lenses**	9,10				9,14
10,1	10,2	10,3	10,4	10,5	10,6	10,7	10,8	10,9	**Groundwater in Valley infill deposits**	10,11			10,14
	11,2		11,4	11,5			11,8		11,10	**Chalk aquifer groundwater**		11,13	11,14
12,1			12,4		12,6	12,7			12,10		**Meteoric water**		12,14
	13,2		13,4	13,5			13,8		13,10	13,11		**Aquifer water**	13,14
14,1	14,2	14,3	14,4	14,5	14,6	14,7	14,8	14,9	14,10	14,11			**Mixed water**

Figure 4.7: Principal Interactions for Components of the Geosphere-Biosphere Sub-system in State S1.

4.3.10 Coupling between Components

Coupling between components is evaluated for the principal components shown in Figure 4.7. These couplings can be distinguished into a limited number of categories. This is illustrated in Table 4.5, which also sets out the processes that would result in these couplings.

Table 4.5: Processes determining the Couplings shown in Figure 4.7

Interactions (Numbered as in Figure 4.7)	Description of the Interactions	Relevant Processes
1,7; 7,1; 2,8; 8,2; 3,9; 9,3; 4,10; 10,4; 5,11; 11,5	Interactions between a solid and its included water	Sorption/desorption; precipitation/dissolution; colloid formation and dissolution; advective and dispersive transport within the solid, including diffusion into intra-particle and inter-particle pore spaces. Relevant both to the composition of the solid and its included water and to the transport of contaminants within the solid/water system.
1,14; 2,14; 3,14; 4,14; 5,14	Effects of a solid on the composition of waters formed by the mixing of meteoric and aquifer waters	Rock-water interactions that modify the chemical composition of waters with different degrees of mixing. Mainly relevant to defining the composition of waters within which contaminant transport occurs.
5,13; 13,5	Interactions between the chalk aquifer and its included groundwater outside and within the GBI that together define the aquifer end-member water that is involved in the mixing process.	Rock water interactions throughout the aquifer, taking into account the composition of the meteoric water that recharges the aquifer at outcrop. Mainly relevant to defining the composition of waters within which contaminant transport occurs.
6,7; 7,6	Exchange of water between flowing streams and soils	Recharge and discharge through the stream banks and bed. Overbank flooding and return flow. Mainly relevant to contaminant transport.
6,9; 9,6	Exchange of water between flowing streams and sand lenses where the latter outcrop in the stream bed or banks.	Recharge and discharge through the stream banks and bed. Overbank flooding and return flow. Mainly relevant to contaminant transport.
6,10; 10,6	Exchange of water between flowing streams and groundwater in valley infill deposits where the latter outcrop in the stream bed or banks.	Recharge and discharge through the stream banks and bed. Overbank flooding and return flow. Mainly relevant to contaminant transport.
6,14; 7,14; 8,14; 9,14; 10,14; 11,14	Mixing of stream waters or groundwaters of various types with pre-existing mixed waters to modify the composition of those mixed waters.	Chemical reactions between waters of differing composition leading to changes in chemical speciation and the formation/dissolution of colloids. Mainly relevant to defining the composition of waters within which contaminant transport occurs.
12,14; 13,14	Mixing of incoming meteoric water or aquifer water with existing mixed waters to modify the composition of those mixed waters.	Chemical reactions between waters of differing composition leading to changes in chemical speciation and the formation/dissolution of colloids. Mainly relevant to defining the composition of waters within which contaminant transport occurs.

Table 4.5: Processes determining the Couplings shown in Figure 4.7 (Continued)

Interactions (Numbered as in Figure 4.7)	Description of the Interactions	Relevant Processes
7,8; 7,10; 8,7; 8,9; 8,10; 8,11; 9,8; 9,10; 10,7; 10,8; 10,9; 10,11; 11,8; 11,10	Flow of water across interfaces between different media	Advective flow of water in both unsaturated and saturated conditions. Relevant to bringing different waters into contact for mixing processes and for the transport of contaminants.
11,13; 13,11	Interactions of the aquifer end-member water within the aquifer zone of the GBI to give modified aquifer water composition. These interactions are shown as bidirectional because it may not be possible to define the completely unperturbed aquifer end-member water.	Chemical reactions between waters of differing composition leading to changes in chemical speciation and the formation/dissolution of colloids. Mainly relevant to defining the composition of waters within which contaminant transport occurs.
12,1; 12,4	Interactions of meteoric waters with soils and valley infill deposits at outcrop leading to direct modification of the solids.	Chemical reactions between meteoric waters and solids leading to weathering of those solids with changes in composition and structure.
12,6; 12,7; 12,10	Interactions of meteoric waters with surface waters and groundwaters.	Inputs of meteoric water affect the flow regime and also give rise to chemical reactions between waters of differing composition leading to changes in chemical speciation and the formation/dissolution of colloids. Relevant both to defining the flow regime and the composition of waters in which contaminant transport occurs.
14,1; 14,2; 14,3; 14,4; 14,5	Effects of mixed waters of various compositions on the structure and properties of solids.	Sorption/desorption; precipitation/dissolution; colloid formation and dissolution.
14,6; 14,7; 14,8; 14,9; 14,10; 14,11	Effects of mixed waters of various compositions on the composition of surface waters and pore waters in various solids.	Chemical reactions between waters of differing composition leading to changes in chemical speciation and the formation/dissolution of colloids. Mainly relevant to defining the composition of waters within which contaminant transport occurs.

The interaction matrix, Figure 4.7, plus the list of processes determining the couplings, Table 4.5, specify the conceptual model for the GBI of State S1 for Lowland Britain unperturbed by human actions.

In Figure 4.7, the evolution of the sub-system through pedogenesis has been excluded from consideration, so the five physical components do not interact directly with each other. Instead they provide a setting in which they condition and are conditioned by their included groundwaters. Interactions between solids and groundwaters from adjacent components are neglected (i.e. interface effects are not considered to be important compared with interactions within components), so it is the flows of waters from one component to another that are the primary controls on both water composition and contaminant transport. The composition of meteoric water is not influenced by any component of the sub-system and the composition of aquifer water is influenced only by the nature of the chalk bedrock and the flow system of the chalk aquifer groundwater.

When perturbations by wells are included, the above system has to be extended to include the well as a physical component and abstracted well water as a water body. In principle, these two components interact with all the other components. However, with a well that abstracts water only from the chalk aquifer, with that water used for irrigation, the key aspects of the interaction matrix are as shown in Figure 4.8.

Soils			1,4					1,9
	Well			2,5	2,6			2,9
		Chalk bedrock		3,5	3,6		3,8	3,9
4,1			Soil water					4,9
5,1	5,2		5,4	Abstracted well water	5,6			5,9
	6,2	6,3		6,5	Chalk aquifer groundwater		6,8	6,9
7,1			7,4			Meteoric water		7,9
		8,3			8,6		Aquifer water	8,9
9,1	9,2	9,3	9,4	9,5	9,6			Mixed water

Figure 4.8: Supplementary Interaction Matrix for Inclusion of a Well in the Geosphere-Biosphere Sub-system in State S1

The structure shown in Figure 4.8 carries over various aspects of Figures 4.6 and 4.7. The physical components are considered to provide a setting for the conditioning of groundwaters. **Soil** conditions **Soil water** and is conditioned by it (1,4 and 4,1). Similarly, the **Well** conditions the **Abstracted well water** and is conditioned by it, e.g. by corrosion of well components (2,5 and 5,2). The **Chalk bedrock** conditions the characteristics of the **Chalk aquifer groundwater** and is conditioned by it (3,6 and 6,3), but the **Chalk aquifer groundwater** is also determined by the composition of the **Aquifer water** end member (8,6). It is debatable whether the influence of the **Chalk aquifer groundwater** on the **Aquifer water** end member should be included (6,8), but this has been done to provide a reminder that it may not be possible to define this end member sufficiently far from the GBI for it to be unperturbed by that system. Furthermore, the **Aquifer water** composition is determined by the physical and chemical nature of the **Chalk bedrock** (3,8), but also determines that physical and chemical nature, e.g. through dissolution reactions (8,3). Both **Meteoric water** and **Abstracted well water** interact directly with **Soils** (7,1 and 5,1) and also mix and react with **Soil water** (7,4 and 5,4). The **Chalk aquifer groundwater** interacts directly with the **Well**, e.g. through corrosion reactions and the precipitation of solids (6,2) and is a major determinant of the characteristics of **Abstracted well water** (6,5). Similarly, the flow and chemical composition of the **Abstracted well water** influence the **Chalk aquifer groundwater** (5,6) and the structure of the **Well** may influence the **Chalk aquifer groundwater**, e.g. by providing a path by which oxygen, nutrients and pollutants may penetrate to depth (2,6). Mixing of the end member waters occurs throughout the system and the composition of **Mixed waters** is determined by the nature of the end members (7,9 and 8,9), the mixing regimes (4,9; 5,9 and 6,9) and interactions with solids (1,9; 2,9 and 3,9). In turn, these mixed waters affect the properties of sub-system solids (9,1; 9,2 and 9,3) and the properties of their associated waters (9,4; 9,5 and 9,6).

The interaction matrices shown in Figures 4.7 and 4.8, plus the associated processes specify the conceptual model for the GBI of State S1 for Lowland Britain perturbed by human actions.

4.4 A LIMITATION OF THE ILLUSTRATIVE EXAMPLE

In discussing the illustrative example set out above and the other illustrative examples described in Appendix B, it was recognised at the second workshop on the project that the focus had been on hydrogeological and hydrogeochemical issues, with much less attention having been given to the interactions of biota with the hydrogeological and hydrogeochemical system. To some degree this was because the GBI was conceived as interfacing with an overlying model of the biosphere, but it is also legitimate to extend the definition of the GBI to include the surface and near-surface biota. If this were done, then additional issues would arise as to how the biogeochemical cycling of water, nutrients, xenobiotic elements and contaminants should be integrated with the hydrogeological and hydrogeochemical representations of transport thought to be applicable at greater depths (recognising that even at these greater depths microbiological processes and organic complexation may be significant considerations). This point is discussed further in the context of the discussion of mathematical modelling in Section 5.

5. DEVELOPMENT AND APPLICATION OF MATHEMATICAL MODELS

The methodology set out in Section 3, as illustrated by the example set out in Section 4 shows how a conceptual model of the GBI or GBIs appropriate to a particular assessment context can be specified. The example applications of the methodology described in Section 4 and Appendix B relate to time-invariant states of the GBI. However, although not illustrated in this project, the methodology also includes an approach to developing conceptual models of transitions between such states. Therefore, the remaining issue to be addressed is the set of mathematical models that are required to implement these conceptual models of GBI states and transitions. The types of model available were described by participants at the two project workshops and the following draws heavily upon the presentations given at those workshops.

Broadly speaking, the types of mathematical model of relevance comprise:

- Structural models, e.g. Digital Elevation Models;
- Landscape evolution models;
- Surface hydrological and near-surface hydrogeological models;
- Models of water, energy and nutrient cycling in biota and near-surface soils and sediments;
- Hydrogeochemical models;
- Thermal transport models (e.g. of permafrost development);
- Landscape models of contaminant transport;
- Coupled models linking several of the above components.

Models of climate change and of ice-sheet development are excluded from the above list. These are of considerable importance, but they require modelling at a global and/or regional scale and set a context for GBI modelling, rather than being used directly in the modelling of a specific GBI. However, they may be used to define boundary conditions used in modelling a GBI, e.g. the presence of an ice-sheet margin close to a location of interest may strongly determine the upper boundary condition for a hydrogeological model representing the GBI. Models of isostatic response and local sea level similarly condition GBI modelling, rather than being integrated into it. These models also require global and/or regional computations. Results from such models can be used locally to simulate land emergence due to isostatic uplift or to define time-dependent base levels for modelling stream incision into the landscape.

5.1 STRUCTURAL MODELS

Structural models define the geometrical framework within which the other types of model are located. In the SKB programme (see Appendix A), one focus is on a model that includes both the surface elevation and the structure and thickness of the overburden (or regolith). This allows the bedrock surface also to be represented. However, structural models are also used to represent the solid rock geology, expressed in terms of rock domains or rock structures, and the various fracture sets that intersect that domain. For example, Posiva has developed an integrated 3D model of the bedrock and overburden in Olkiluoto (BIOPROTA, 2014). Essentially, such models are directly based on observations from site characterisation, but they may include the capability for change as the landscape develops. For example, in the SKB approach (see Appendix A, Section A.3.3), as isostatic uplift results in land emergence, the distribution and thickness of deposits is modified by changing patterns of erosion, transport and deposition in coastal waters. Also, following emergence, lakes are slowly transformed into wetland areas through infilling by organic deposits. Thus, structural models may be closely linked to landscape development models.

5.2 LANDSCAPE DEVELOPMENT MODELS

From the review of national programmes included in Appendix A, two general types of landscape development were identified as being of most interest. The first of these comprises development of a coastal landscape as a result of isostatic uplift, which is the focus of work by SKB and Posiva, due to the relatively rapid rate of uplift that is still occurring in response to the crustal depression induced by ice-sheet loading as a consequence of the Weichselian glaciation (MIS 2, with a maximum at around 18 ka BP) (see Figure 5.1). The second general type of landscape development of interest is fluvial incision into a palaeosurface. This may be a limestone plateau, as in the case of the Bure site in Eastern France (Appendix A, Section A.5.2) or a lowland landscape draped with glacial till (Appendix B, Section B.3.2). It is emphasised that these are not the only forms of landscape development that may be of interest. For example, at Yucca Mountain, consideration has been given to the combination of block uplift and gully erosion that could reduce the thickness of cover overlying the proposed spent fuel repository on a timescale of one million years [Stüwe et al., 2009].

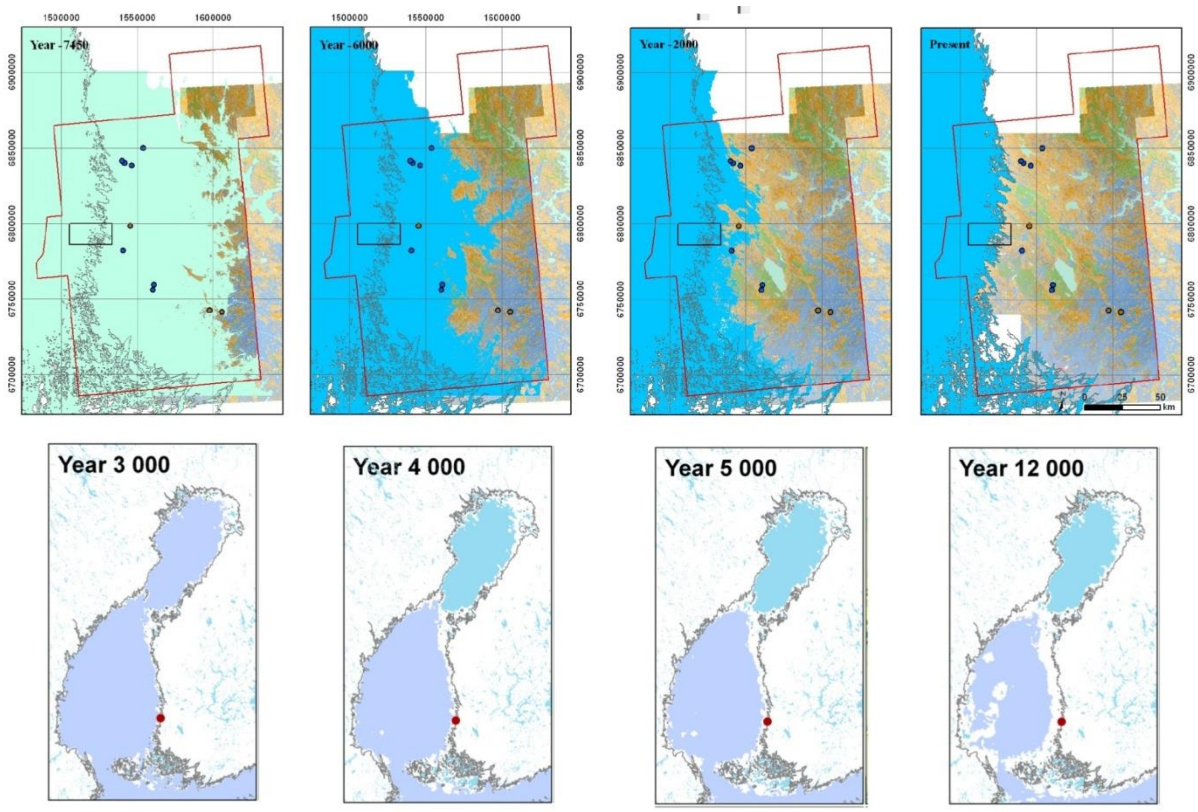


Figure 5.1: Past Land Uplift Development of the Reference Area according to Model Projections (upper panel) and Future Development of the Gulf of Bothnia and of the Olkiluoto Site according to the Reference Case in the Biosphere Assessment (lower panel). [BIOPROTA, 2014]

In respect of incision, several climatic factors may directly influence fluvial deposits. These include the intensity of precipitation and its seasonal distribution. According to Vanderberghe and Woo [2002] extreme storm events have a much larger impact on sediment deposition than does “regular” precipitation throughout the year. This is supported by the classification of rivers in high latitudes, which is largely determined by the amplitude and duration of peak flows and not by mean temperature or mean precipitation [Church, 1983; Woo, 1986]. Snow and ice may also be important controls on sedimentation, as they have the ability to dam rivers. In addition, water released during rapid thawing of the snow and ice greatly contributes to the peak runoff during spring break-up [e.g. McCann et al., 1971]. An example of an indirect effect of climate on fluvial development is permafrost [Vandenberghe, 2003; Blum and Törnqvist, 2000]. Frozen ground reduces the permeability of the soil therewith enhancing surface runoff and concentrating it in a short time period [Church, 1983, Woo, 1986]. However, there may be less total (surface and subsurface) runoff and increased sublimation plus evaporation. During cold climates, most runoff may occur as overland flow, whereas, in the same locations and during warmer climates, runoff would be subsurface [Blum and Törnqvist, 2000]. This contrast arises because of the small capability of the permafrost for groundwater storage [Woo and Winter, 1993]. The high surface runoff during thawing of the permafrost leads to higher stream densities [Kasse, 1997] during thawing. This also has an impact on total sediment availability and transport [Bogaart, 2003]. Slope stability would possibly also be affected due to an increased pore-water pressure during thawing of the permafrost [Andres et al., 2001]. Taking the above considerations into account, it is clear that sediment delivery to arctic and subarctic rivers is largely determined by the presence or absence of permafrost.

In the case of both isostatic uplift and incision, current models are largely empirical. In the case of uplift, the rate of uplift may be quantified, but the description of how the landscape develops is largely based on observations of analogous situations. For example, at Forsmark, distinctions with distance inland, e.g. in respect of lake development, are taken as analogous to future developments in time at a specific location. This is a generally adopted principle in geomorphology, where distinctions in space at a specific time are treated as corresponding to differences in time at a particular location. In the case of incision, the relative degree of incision into palaeosurfaces of different age may be used to construct an empirical model of long-term rates of incision (Appendix B, Section B.3.2).

5.3 SURFACE HYDROLOGICAL AND NEAR-SURFACE HYDROGEOLOGICAL MODELS

3D modelling of the surface hydrological and near-surface hydrogeological domain is becoming a mature discipline. Physically based, surface-water catchment models were initially developed in the 1980s (Abbott et al., 1986a; 1986b), leading to the development of the SHETRAN (http://research.ncl.ac.uk/shetran/) and MIKE SHE modelling systems. In particular, the MIKE SHE/MIKE11 modelling package has been extensively used in safety assessment related studies by SKB and is being actively explored as a modelling tool by RWMD [Bosson et al., 2010; Towler et al., 2011; Berglund et al., 2013]. Simulations of surface hydrology and near-surface hydrogeology with these tools typically use high resolution climate data (with precipitation specified over 15 minute to 1 hour intervals) and require spatially distributed information (grid cells may be of as little as a few tens of metres across and would seldom be more than a few hundred metres). Future projections of climate cannot be made at this degree of spatial or temporal resolution, so data from instrumental records at suitable analogue stations are used or alternatively weather generators can be used to simulate such instrumental records, conditioned by the broad characteristics that can be specified in long-term projections of future climate.

An important area that was explored in presentations by SKB at both the first and second workshops [BIOPROTA, 2013b; 2014] was the modelling of sub-surface hydrogeology under permafrost conditions.

A number of simulation scenarios for different climate and permafrost conditions at different depths were performed with MIKE SHE. These were identified as:

- 1b = shoreline at10000AD, temperate (present) climate;
- 2a = shoreline at 10000AD, Arctic periglacial climate, no permafrost;
- 2b = shoreline at 10000AD, Arctic periglacial climate, 100 m permafrost;
- 2c = shoreline at 10000AD, Arctic periglacial climate, 240 m permafrost.

The model area is shown in Figure 5.2 (red boundary) with the location of present and future coastlines also shown. The drainage network existing at the present and projected for the future are shown (blue) and the locations of future taliks are shown for the two permafrost scenarios.

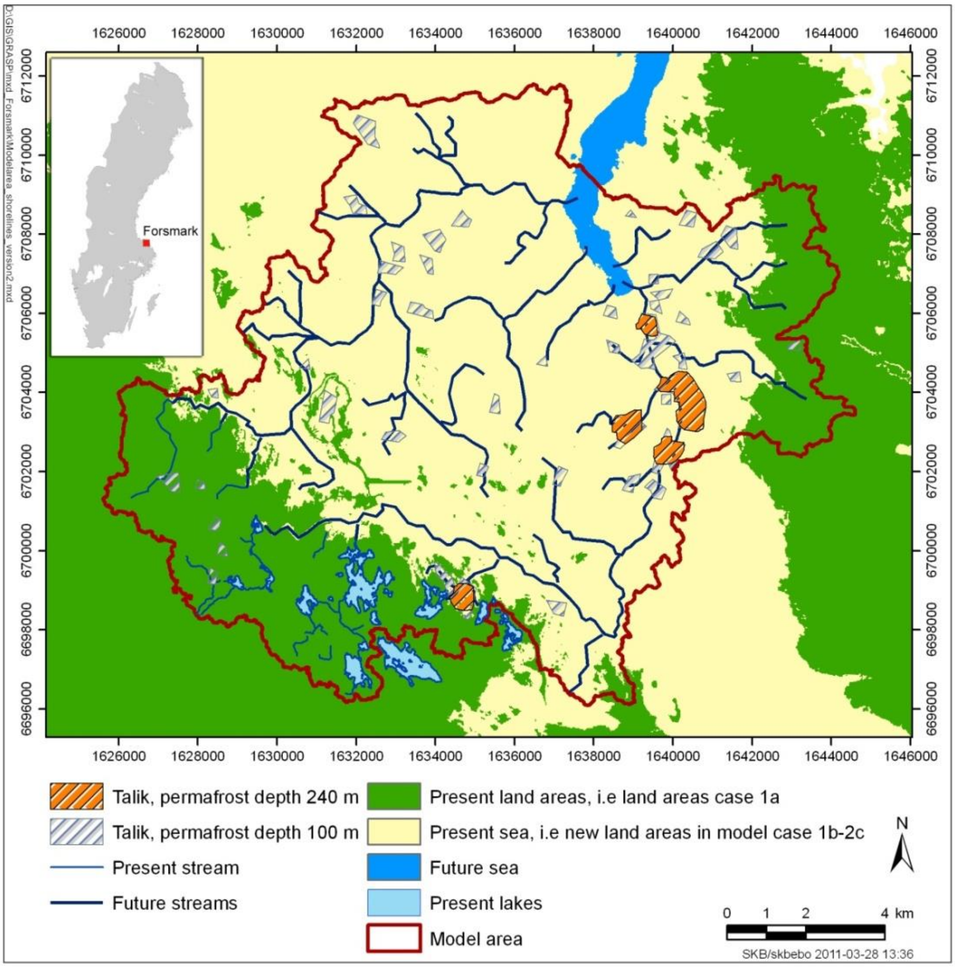


Figure 5.2: Model Area for the Simulations of Particle Releases showing the Locations of Taliks (from Bosson et al., 2012a).

A comparison of vertical groundwater flows between ConnectFlow and MIKE SHE models of this system was carried out for the temperate scenarios (not shown) and indicated that they were comparable. Results show generally decreasing vertical groundwater flow with depth, and smaller vertical flow under permafrost conditions than under unfrozen conditions (Figure 5.3). The overall pattern of both the vertical and the horizontal groundwater flow, and the water exchange between the deep and shallow groundwater systems also changed dramatically in the presence of permafrost compared with unfrozen conditions.

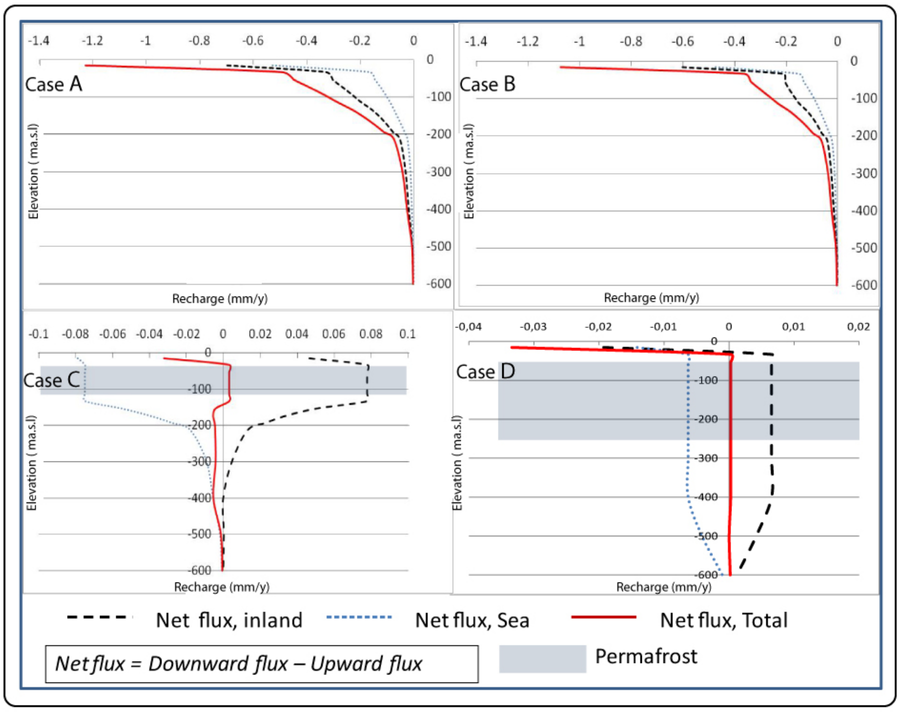


Figure 5.3: Vertical Groundwater Flux in Areas corresponding to Taliks as a Function of Elevation for all Simulation Cases (A, B, C and D), from Bosson et al. (2012b). Net recharge (in mm/y) is calculated as total recharge minus total discharge at different elevations. Cases A, B, C and D correspond to temperate conditions and periglacial conditions with no permafrost, 100 m of permafrost and 240 m of permafrost, respectively. Net fluxes are shown separately for inland and sea areas. The unfrozen bedrock under the sea acts as the main discharge area.

Negative values indicate an upward groundwater flux. Talik areas are dominated by upward groundwater flow under temperate conditions. Many of the inland taliks turn into areas with net downward groundwater flux under periglacial conditions. The unfrozen bedrock under the sea acts as the main discharge area.

However, although the vertical groundwater flow decreases significantly in the presence of permafrost, there is still an exchange of water between the unfrozen groundwater system below the permafrost and the shallow groundwater in the active layer, via taliks. ‘Through taliks’ tend to prevail in areas that constitute groundwater discharge zones under unfrozen conditions, which then mostly shift to net recharge zones (through taliks with net downward flow) under permafrost conditions.

Particle tracking simulations were performed for cases 1b, 2b and 2c under the following boundary conditions:

- Varying climate and permafrost depths but using the same landscape (shoreline);
- Particle release took place in the bedrock at 400m depth, with release restricted to the land portion of the model area. No particles were released close to the model boundary;
- 5 particles per cell were randomly introduced in the layer at 400 m depth, with the same number of particles and depths for all cases;
- Simulation time was 5000y, i.e. one year is cycled 5000 times;
- In total 100,570 particles were released in each simulation.

The particle exit locations are shown in Figure 5.4.

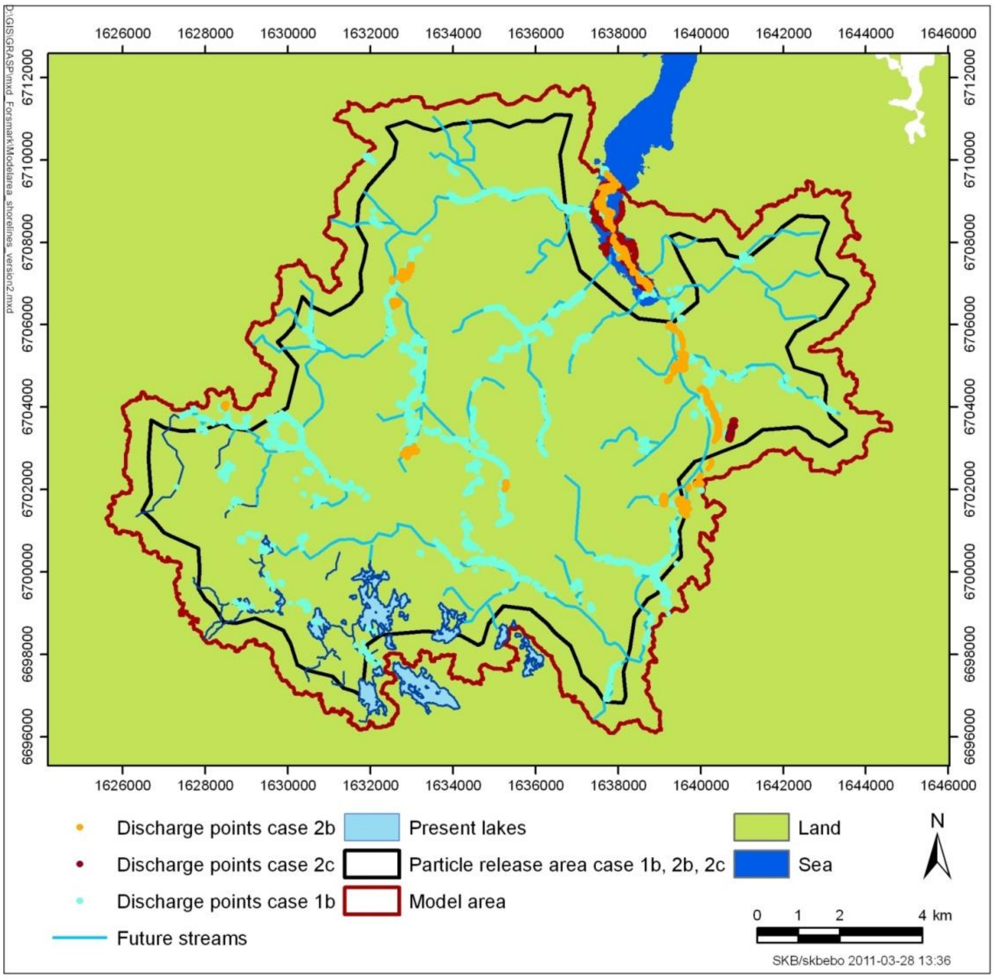


Figure 5.4: Particle Exit Locations for the Three Particle-tracking Simulations. Figure provided by SKB.

The nomenclature used to describe the particle-transport pathways is illustrated in Figure 5.5. In the unfrozen case A, the transport and associated breakthrough curves are subdivided into three components (breakthrough components; BCs), where one is for the transport down to −50 m into the bedrock (which is CP 1 for the downward transport from the surface to that bedrock depth, i.e., for BC

1), the second is for the transport through the underlying bedrock and back to the −50 m depth level (which is CP 2 for the essentially horizontal-to-upward transport to that bedrock depth, i.e., for BC 2), and the third is for the transport from −50 m up to the Quaternary deposits (the bottom of which is CP 3 for the upward transport, i.e., for BC 3). For permafrost cases C and D, the breakthrough curves are also subdivided into three components, including the transport: (1) from recharge in the active layer through the frozen bedrock (the bottom of which is CP 1 for the downward transport from the active layer, i.e., for BC 1) (2) through the unfrozen system beneath the permafrost (the bottom of which is CP 2 for the essentially horizontal-to-upward below-permafrost transport, i.e., for BC 2), and (3) from the bottom of the permafrost up to the active layer (the bottom of which is CP 3 for the upward transport, i.e., for BC3).

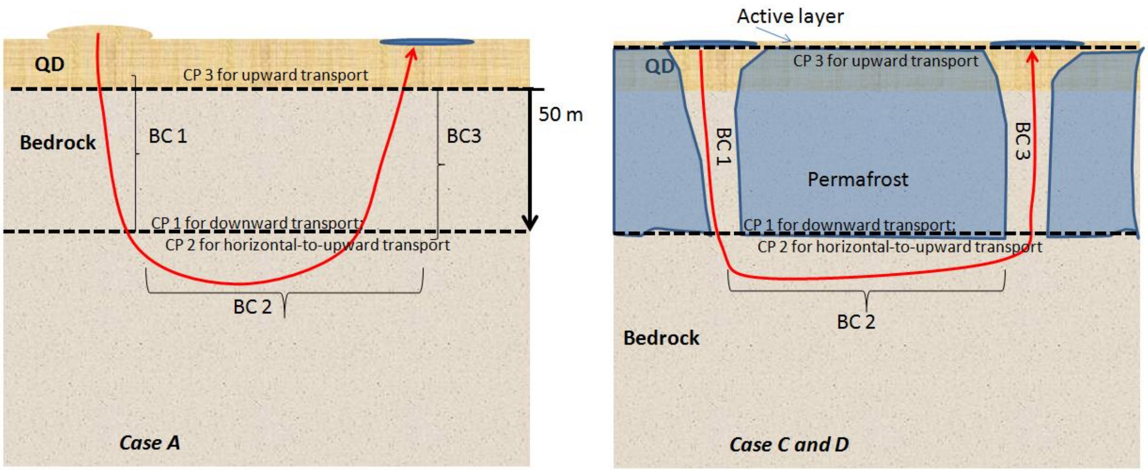


Figure 5.5: Particle Release in Recharge Areas on the Ground Surface for Temperate Climates and Periglacial Climates with and without Permafrost (from Bosson et al., 2012b).

In the temperate Case A, there are many local flow systems with upward and downward groundwater flow (Figure 5.5). When permafrost is present, the movement of deeply released particles under the permafrost is preferentially horizontal and becomes vertical only once the particles reach a through talik with upward groundwater flow (Figure 5.6). In both permafrost cases C and D, many pathways are closed. The longest travel times (slowest breakthrough component) are in the unfrozen system below the permafrost, while the shortest travel times (fastest breakthrough component) are in the taliks through the permafrost both for the recharging particles (going from the Quaternary deposits to the unfrozen bedrock) and the discharging particles (going from the unfrozen bedrock back to the Quaternary deposits.

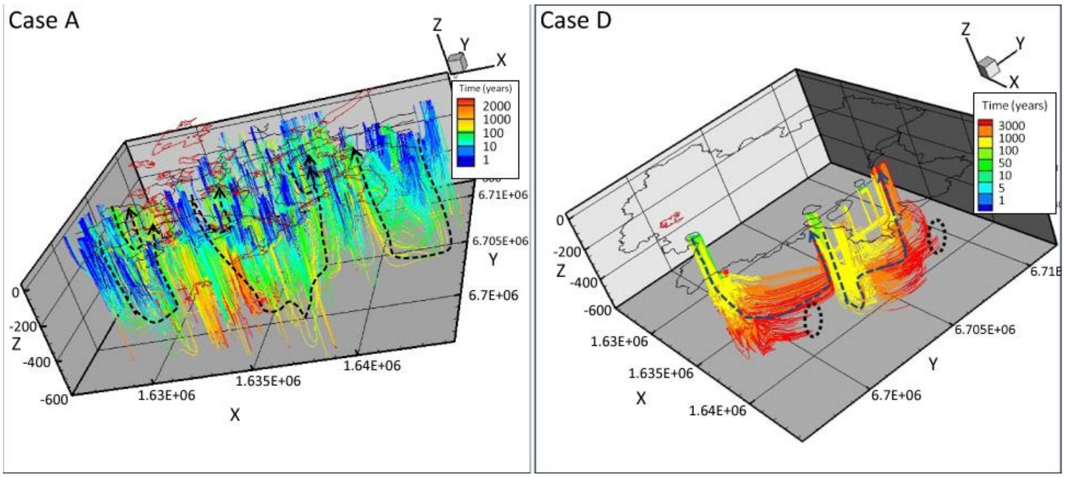
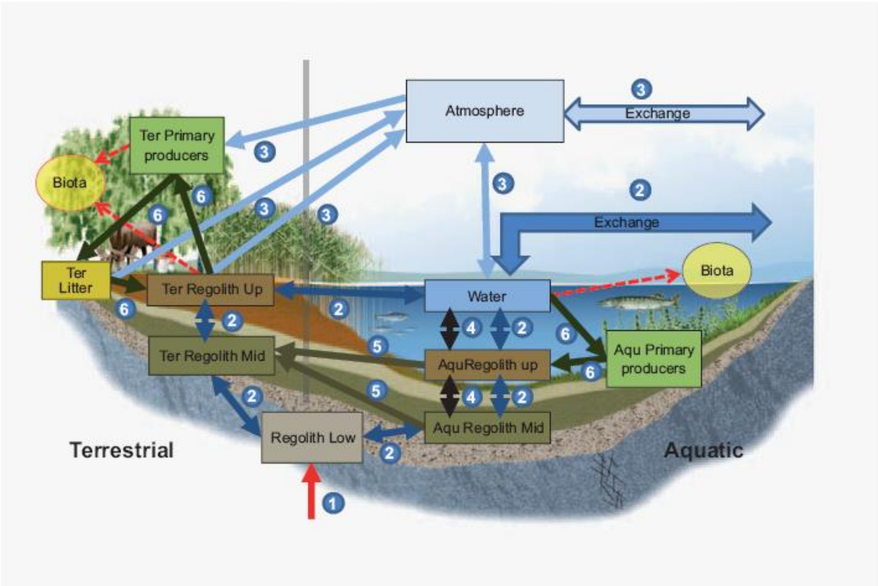


Figure 5.6: Particle Pathways from Release at the Surface down to and through the Bedrock towards a Net-discharge Talik Area and back to the Quaternary Deposits, for Simulation Cases A and D (from Bosson et al., 2012b). The colours quantify the travel times along each particle pathway.

This modelling indicates the level of detail that is achievable in 3D hydrogeological modelling and a similar degree of resolution is available in the modelling of surface hydrology. However, it should be noted that in this model the development of permafrost is not modelled. Instead, particular ‘snapshot’ distributions of permafrost are imposed and groundwater flow paths are computed under these prescribed conditions. In particular, although plausibility arguments are provided justifying the locations of the through taliks, development of through taliks in those locations is not demonstrated by explicit modelling. Furthermore, the model simulates the movement of unretarded ‘particles’ of water through the hydrogeological system. Thus, it does not address the movement of contaminants and how they would be retarded by interaction with the rock. If that retardation can be represented by an equilibrium distribution coefficient, it is straightforward to derive the retarded travel time from the unretarded travel time. However, if kinetic and spatially varying geochemical effects on sorption need to be taken into account, the hydrogeological model needs to be coupled to a suitable geochemical model. The possibility for coupling hydrogeological, thermal and geochemical models in a single, all-encompassing modelling framework is discussed in Section 5.8.

5.4 MODELS OF BIOGEOCHEMICAL CYCLING

In ecosystems, there is a continual cycling of energy, water, nutrients and xenobiotic elements between the various components (plants, animals, water bodies, and soils and sediments). Contaminants such as radionuclides may be incorporated into these various cycles, with the important cycles in specific cases being determined by the chemical and biochemical characteristics of the contaminant. This type of modelling was discussed to only a limited degree within the project, but it is an intrinsic part of the SKB approach, as discussed in Appendix A and illustrated in Figure 5.7.



Model name	Description
Regolith Low	The lower part of the regolith overlying the bedrock, primarily composed of till. It is common to the terrestrial and aquatic parts and its origin is from the glaciation.
Aqu Regolith Mid	The middle part of the regolith in the aquatic part of biosphere objects, usually consisting of glacial and postglacial clays, gyttja and finer sediments which originate mainly from the period after the retreat of the glacial ice sheet, or from later resuspended matter mixed with organic sediments.
Aqu Regolith Up	The part of the aquatic regolith with highest biological activity, comprising c. 5–10 cm of the upper aquatic sediments where resuspension and bioturbation can maintain an oxidising environment.
Ter Regolith Mid	The middle part of the terrestrial regolith, containing glacial and postglacial fine material, i.e. former sediments from the seabed / lake bottoms.
Ter Regolith Up	The upper part of the terrestrial regolith which has the highest biological activity, like the peat in a mire, or the plowing layer in agricultural land.
Litter	Dead plant material overlying the regolith.
Water	The surface water (stream, lake, or sea water).
Aqu Primary Producers	The biotic community in aquatic habitats, comprising both primary producers and consumers.
Ter Primary Producers	Terrestrial primary producers.
Atmosphere	The lower part of the atmosphere where released radionuclides are fully mixed.

Figure 5.7: Conceptual Illustration of the Radionuclide Model for a Biosphere Object. Boxes represent compartments, thick arrows fluxes, and dotted arrows concentration computations for non-human biota (these are not included in the mass balance). The model represents one object which contains an aquatic (right) and a terrestrial part (left) with a common lower regolith and atmosphere. The source flux (1 Bq/y) is represented by a red arrow (1). The radionuclide transport is mediated by different major processes, indicated with dark blue arrows for water (2), light blue for gas (3), black for sedimentation/resuspension (4), dark brown for terrestrialisation (5), and green for biological uptake/decomposition (6). Import from and export to surrounding objects in the landscape is represented by arrows marked "exchange". Brief descriptions of the compartments are given in the table below the figure. Based on Figure 13-6 and Table 13-1 of SKB [2011].

Essentially, this approach to modelling is based on quantifying the 'pools' and fluxes of elements such as carbon in the environment and then modelling the transport of contaminants between the same pools by introducing discrimination factors between the transport of those contaminants and the primary constituent represented by the pools and fluxes.

5.5 HYDROGEOCHEMICAL MODELS

Hydrogeochemical models are generally required to represent the mixing of waters of different types and the modification of the chemical characteristics of those waters. Mixing models require the identification of a limited number of end-member waters. Field observations are then interpreted in terms of linear combinations of these waters to match the multi-component characteristics of the observed waters. Mismatches between the results of applying such a mixing model and the observed compositions of groundwaters can often be interpreted in terms of chemical reactions between the mixed waters, or water-rock interactions. Such reactions can be simulated at a point scale using codes such as PHREEQC (http://wwwbrr.cr.usgs.gov/projects/GWC_coupled/phreeqc/) and Geochemists Workbench (http://www.gwb.com/). Indeed, with PHREEQC, 1D transport modelling can also be undertaken. Furthermore, PHREEQC can be embedded within a 3D hydrogeological model of the system of interest (see Section 5.8).

5.6 THERMAL TRANSPORT MODELS

As discussed in Sections 3 and 4, heat input from the repository is seldom of relevance in characterising the GBI. The principal boundary conditions for modelling are the ground surface temperature, which may be somewhat different from the air temperature due to factors such as vegetation and/or snow cover, and the geothermal heat flux from below. As discussed in Section 5.3 and in Appendix A, for proposed repositories in various northern European countries (notably Sweden and Finland), the potential development of permafrost is of relevance in post-closure safety assessments, but it should also be kept in mind that seasonal ground freezing can also significantly impact the hydrological regime and hence contaminant transport in the environment. In general, hydrogeological and contaminant transport models do not include the transport of heat, although the transport equations for heat are very similar to those for contaminants, so such an extension is relatively straightforward to implement, as has been done in one version of SHETRAN [Anderton and Ewen, 1996; Birkinshaw and Ewen, 2004; Ewen et al., 2004]. Often, permafrost development has been modelled using 1D, 2D or 3D models of heat transport, neglecting the associated redistribution of groundwater and potential changes to groundwater composition due to solute expulsion on freezing.

Model studies of present and future permafrost development influenced by increasing atmospheric greenhouse-gas concentrations can be found in e.g. Lunardini [1995], Kukkonen and Šafanda [2001] and Slater and Lawrence [2013]. Additionally, some model studies on the thermo-hydro-mechanical impacts of freezing processes on bedrock properties with implications for interactions between glaciers and permafrost in a time frame of a glaciation cycle (~100 ka) have been conducted, e.g. Bauder et al. [2003], Hartikainen [2004], SKB [2006], Person et al. [2007], Lemieux et al. [2008a, 2008b, 2008c], Hartikainen et al. [2010] and Hartikainen [2013]. The effects of freezing of the geosphere on groundwater flow have been studied by e.g. Vidstrand et al. [2010] and Bosson et al. [2012a; 2012b].

5.7 LANDSCAPE MODELS OF CONTAMINANT TRANSPORT

In the assessment studies undertaken by SKB and Posiva (see Appendix A), the landscape is distinguished into a set of biosphere objects. Radionuclide discharges from the geosphere are taken to occur into one or more of these biosphere objects, and radionuclide transport between the objects is determined by surface-water flow rates between those objects. An illustration of how the landscape is represented in terms of a limited number of such biosphere objects (or aggregated super-objects) is shown in Figure 5.8. The typical internal structure of a single object is as shown in Figure 5.7, or illustrated more schematically in Figure 5.9.

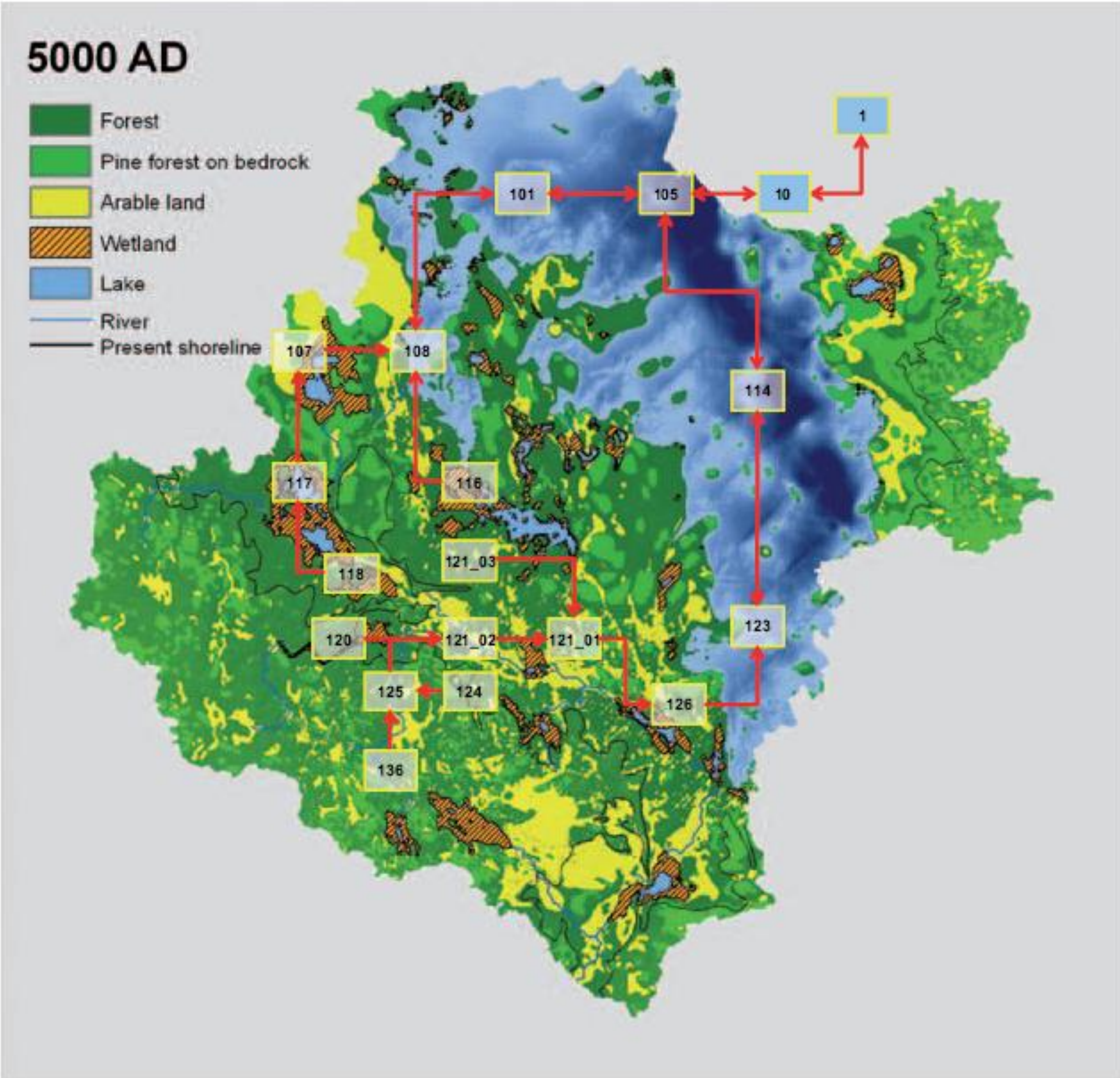


Figure 5.8: The Location and Hydrological Connections of Biosphere Objects in the SR-Site Assessment, displayed on a Map of the Forsmark Landscape at 5000 AD. Figure 13-5 of SKB [2011].

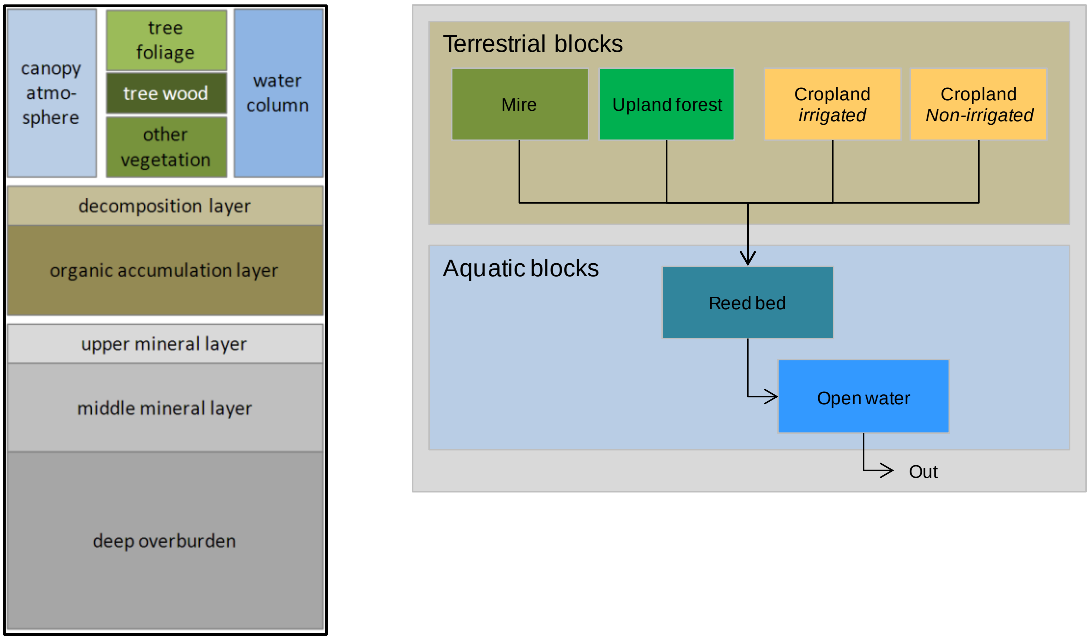


Figure 5.9: Left: the Common Structure for Modelling any Biotope in any Ecosystem Type in a Biosphere Object. Right: The General Ecosystem Structure of 'Super-objects'. Figure 5-9 of Posiva [2012].

Landscape models of this type comprise zero-dimensional representations of the individual objects connected to give a crude 2D representation of the overall landscape, with transport conditioned by water flows estimated from either 2D or 3D hydrological and hydrogeological modelling. Thus, they illustrate how a 3D understanding of the landscape can be used to develop a simplified, abstracted and lower dimensional model for use in assessment studies. Furthermore, this simplified model can be re-specified and a sequence of time steps as the landscape develops, allowing transient calculations of radionuclide transport and accumulation in an evolving environment to be undertaken.

5.8 COUPLED MODELS

In some circumstances, use of the models of individual aspects of the GBI, as discussed in Sections 5.1 to 5.7 will not be adequate to address all the issues arising in an assessment context. Specifically, issues may arise as to the effects of coupling between those various aspects, particularly when that coupling is bi-directional and non-linear. A good example is the relationship between permafrost development, groundwater flow, heat transport and solute exclusion from ground ice. To address such issues a more comprehensive modelling framework is required. An important development in this area relating to reactive transport modelling is being undertaken by Amphos21 and was described at both the workshops [BIOPROTA, 2013b; 2014].

Reactive transport modelling performed by Amphos21 on behalf of SKB was reported in SKB publication R-10-30 [Piqué et al., 2010]. In that project, a relatively advanced geochemical approach was applied. Numerical calculations were developed to allow radionuclide transport to be quantified with the in-growth of daughters being coupled with the transport calculations. Hydrology was, however, oversimplified and was not fully representative of site conditions. It was, therefore, identified that improvements to the approach were required and the use of more advanced technology or 'super computers', was considered. The current approach being developed by Amphos21 has a greater emphasis on the scientific basis than on the technology used for simulation. Thus, modelling capabilities may be improved through use of more advanced technology.

COMSOL Multiphysics (http://www.comsol.com/; http://en.wikipedia.org/wiki/COMSOL_Multiphysics/), a high-performance computing platform, has been investigated. The platform was initially designed for mechanical engineering applications, but capabilities have been further improved and developed. The main platform, which allows continuing processes that are represented by partial differential equations to be solved, is supported by a number of interfaces with sub-modules (Figure 5.10). There is no specific module for reactive transport; rather there is a split between linear and non-linear phases with the tool being less efficient for the non-linear phase. The model is therefore being coupled with a PHREEQC (http://wwwbrr.cr.usgs.gov/projects/GWC_coupled/phreeqc/) step allowing questions relating to both physics and chemistry to be addressed whilst being fully coupled with thermodynamic modelling capabilities. The code has been tested against other codes at different development stages.

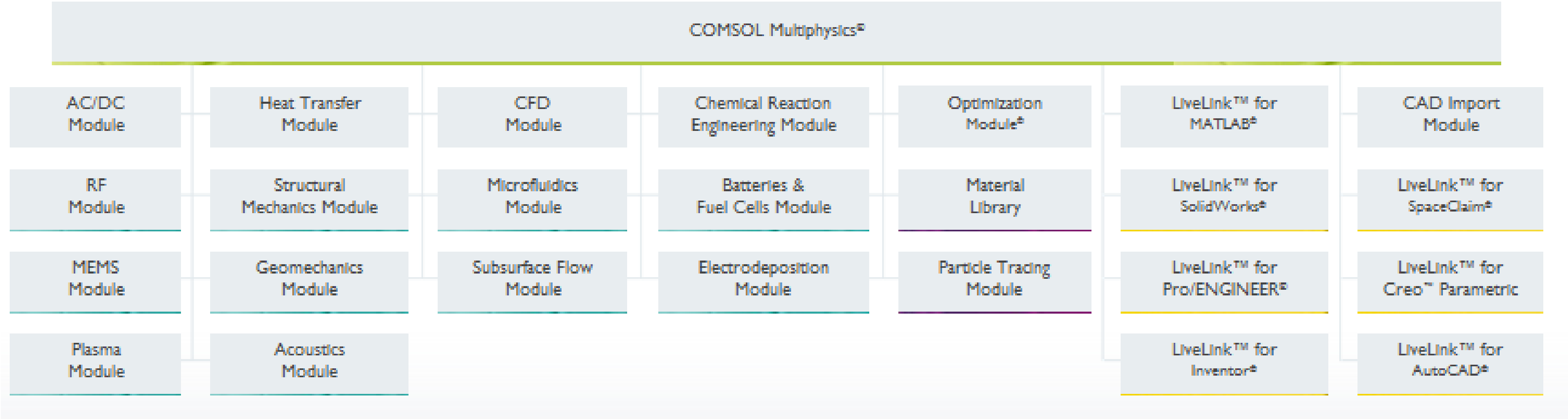


Figure 5.10: The COMSOL Multiphysics Platform and supporting Module Interfaces.

The coupled approach has been largely financed by Andra and was first applied to evaluate caesium migration from a disposal cell and retention in engineered barriers under increasing bicarbonate concentrations that are determined by steel corrosion. To show its potential applicability to the GBI, a trial was run based on a hypothetical scenario as a means of demonstrating capabilities.

In the scenario, a lake was incorporated within a digital elevation model to act as a discharge zone above Quaternary till deposits. There was fine discretisation, particularly in the area immediately around the lake where dynamics would be most important. The difference in transport between a conservative tracer and radionuclides placed in the fracture zone was investigated with a large difference observed: the conservative tracer was transported rapidly to the surface lake whereas radionuclides were retained to a greater extent through sorption onto clay minerals. The demonstration illustrated that the methodology can be applied to GBI scenarios.

Subsequently, further work was undertaken using iCP (the COMSOL-Phreeqc interface) to simulate mechanistic radionuclide reactive transport processes under realistic (three-dimensional, heterogeneous) hydrological conditions. A trial application of the approach to two marine basins at the Forsmark site was illustrated at the second workshop [BIOPROTA, 2014], giving details of the model structure, gridding and parameterisation. Results of model calculations for ^{90}Sr, ^{137}Cs and ^{235}U were presented.

It was concluded, that advanced computational technologies are available and can be applied, in principle, to GBI problems and can be coupled with scientific advances relating to radionuclide migration and near-surface hydrogeology. By explicitly representing chemistry within the coupled model, processes such as re-concentration and back diffusion could be evaluated. However, a limitation is the availability of values for the required parameters: the focus for the generation of model data has largely been on requirements for simpler model approaches. Where data, such as K_d values, have been derived for the right geochemical conditions, this could be used to calibrate models, but there is a general need to look again at data requirements, availability and derivation.

An alternative to the use of super computers would be enhanced software. However, one of the large advantages with platforms such as COMSOL Multiphysics is the expertise of the model developers in terms of numerical problems and how to solve them, i.e. the software approach is already likely to be close to optimal. In principle, it is possible to incorporate the whole system (fracture network, Quaternary deposits, turnover rates for different types of material etc.). However this would be a time consuming and costly development, hence coupling of different tools may be a more efficient way forward with the output of one model being used as input into the next: effective communication between model interfaces would be required, and careful consideration would need to be given to whether processes were loosely or tightly coupled, and whether the coupling was unidirectional or bidirectional). It would, in principle, be possible to consider radionuclide transport under changing landscape conditions. However this may require an adaptive mesh approach, which has been used previously to enable human heart model simulations. Such an approach would allow the effects of land rebound to be evaluated.

5.9 OVERALL POSITION ON MODELLING THE GEOSPHERE-BIOSPHERE INTERFACE

The information presented above shows that a wide range of mathematical and computational tools are available for addressing issues relating to the GBI. It seems likely that most such issues could be addressed using these tools individually or in combination. Possibly one exception is in respect of landscape development, where existing models are primarily descriptive, rather than process-based. However, the enhancement and application of landscape development models under changing climatic conditions is being addressed within the framework of MODARIA Working Group 6, so it is not considered further here.

The other main issue to be addressed is the integration of the various modelling tools to address situations in which complex, non-linear feedbacks arise, e.g. in the context of the development of permafrost. In the context of modelling ground freezing, changes in hydrogeology and solute expulsion, there is already modelling experience available, so no fundamental issues appear to arise. A less well developed area is the integration of models of biogeochemical cycling into a wider hydrogeological and hydrogeochemical context. Here, one of the issues is that organic materials are typically heterogeneous and poorly characterised chemically. Therefore, including organic materials directly into a general geochemical modelling tool is unlikely to be a viable option. Indeed, it may be more sensible to approach this issue through specific consideration of a limited number of radionuclides of particular importance in performance assessments, e.g. C-14, Cl-36, Se-79 and I-129, so that well posed questions can be developed relating to the geochemical and biological processes controlling their transport and distribution in the GBI (defined to include both surface soils and the associated vegetation).

It is clear that integration of modelling tools can be facilitated through the use of platforms such as COMSOL Multiphysics and this is an area deserving of intense effort over the next few years. An impressive start has been made in this area by Amphos21 and this provides a good basis for such further developments. A potential way forward is to use the methodology set out in Section 3 to develop conceptual models for GBIs of interest and then to investigate how those conceptual models could be implemented using existing mathematical modelling tools or adaptations of them within a platform such as COMSOL Multiphysics.

6. CONCLUSIONS AND RECOMMENDATIONS

The current project commenced in December 2012. Thus, within 18 months a substantial amount has been achieved. Previous work on the GBI in various national programmes has been reviewed; a structured methodology for developing conceptual models of GBIs of various types has been developed; applications of that methodology have been made; and consideration has been given to the range of mathematical and computational tools that are available for implementing the conceptual models. In addition, an account of the proposed methodology has been published in the peer-reviewed literature [Smith et al., 2013]. Also, the two workshops held as part of the project facilitated discussion on a wider range of issues than are covered in this final report on the project, which is focused on those matters directly relevant to developing conceptual and mathematical models of the GBI in different contexts.

The following subsections draw some general conclusions from the study, but it is emphasised that many additional, more detailed conclusions and observations are included in the preceding sections.

6.1 DEFINITION OF THE GEOSPHERE-BIOSPHERE INTERFACE

a) In the real world there is no entity that would be generally described as the GBI. Furthermore, in developing a descriptive model of a specific site there may be no need to include a distinct component of the description relating to the GBI. Rather, discipline-specific descriptions, e.g. of the solid geology, hydrogeology, hydrogeochemistry, overburden characteristics and ecosystems, may be appropriate, with each description applicable to a spatial domain appropriate to that discipline. This suggests that the role of a GBI may first emerge when the overall disposal system is being conceptualised for assessment-modelling purposes. Even at this stage, it may not be necessary to specifically develop a conceptual model of the GBI. For example, the hydrogeological and hydrogeochemical model may extend from below repository depth to the ground surface and may interface directly with a biosphere model based on the biogeochemical cycling of elements in ecosystem components. However, this example illustrates the potential utility of a conceptual and mathematical model of the GBI. Such a model might represent the region between the upper part of the host rock and the overlying soil-plant system, such that it addresses the transition zone between the domain in which contaminant transport is dominated by hydrogeological and geochemical considerations and the domain in which contaminant transport is dominated by surface hydrological and biotic processes.

b) Although the GBI may be found useful in conceptual modelling, this utility may not carry over into mathematical modelling, where various tools may be employed to evaluate the significance of various subsets of processes identified as being of potential significance. The conceptual model of the GBI may be used either to inform development of such mathematical modelling tools, or to audit the existing set of available tools to determine whether they adequately represent the key components of the GBI and the interactions between them that are identified in the conceptual model.

c) The GBI adopted will depend on both the specific or generic site to be assessed and the requirements that are placed upon the assessment. Although the GBI can, in principle, be defined both for deep and shallow disposals of solid radioactive wastes, in practice, in the case of shallow disposal, the repository is likely to be embedded in a zone that is relatively stable, but that is susceptible to significant change over the assessment period. Thus, the repository may be considered to be embedded in the GBI rather than being located in the geosphere below it. This may apply particularly where the repository is excavated from the surface, since all the overlying materials will necessarily have been engineered to some degree, so the engineered facility could be considered to extend from depth to the surface.

d) Because the GBI or GBIs adopted will be system specific, it is useful to consider the extent to which GBI characteristics might differ between various contexts. Such a consideration is likely to be facilitated by use of the typography of different types of disposal system that is being developed by IAEA's MODARIA Working Group 6.

e) Within the overall context of interglacial conditions, there are a wide variety of GBIs that require consideration. These broadly divide into two classes, i.e. those associated with wells and those associated with groundwater discharge. In the case of wells, there is little evidence that the time development of the environment needs to be taken into account, but for groundwater discharge the timescales of landscape development may be comparable with the timescales over which radionuclides move through the GBI and an explicit representation of that landscape development may be required. This leads to the need to develop rules for mapping radionuclides from one component of the environment to a different component as the landscape changes.

f) In many circumstances, it will be appropriate to define the GBI to encompass the whole region down from the ground surface to some depth in the host rock. However, it was noted that, in other contexts, it may be useful to focus on a region with an upper boundary some distance below the ground surface, so that the focus is on hydrogeological, hydrogeochemical and geomicrobiological processes. In this context, it was emphasised that further work is required on characterising and modelling geomicrobiological processes of relevance.

6.2 DETERMINISTIC OR STOCHASTIC MODELLING

g) Stochastic modelling is widely used in simplified overall assessment models. However, these models are often underpinned by detailed, process-based models, with results or simplified models abstracted from these detailed models for use in assessment studies. The complexity of the detailed models means that they are typically used in deterministic mode, with the robustness of the results obtained explored in single or multi-parameter sensitivity studies. In this report, the focus has been on the development of conceptual models of the GBI and how these may be translated into comprehensive, process-based mathematical models. These models would typically be used in exploratory studies to determine the principal controls on assessment results and thus to inform the implementation and parameterisation of simpler, assessment-level models.

6.3 APPLICATION OF THE METHODOLOGY

h) The overall methodology set out in Section 3 is intended to be applied within the framework of a specific assessment context, with the assessment context comprising the various components set out in BIOMASS [2003].

i) The methodology for development of a conceptual model of the GBI for transitions between two states of the system has only been explored to a limited degree on the current project. In general terms, the proposed methodology for representing transitional states of the GBI follows that for representing transitional states of the biosphere in BIOCLIM [2004].

6.4 MATHEMATICAL MODELLING

j) A wide range of mathematical and computational tools is available for addressing issues relating to the GBI. It seems likely that most such issues could be addressed using these tools individually or in combination. Possibly one exception is in respect of landscape development, where existing models are primarily descriptive, rather than process-based. However, the enhancement and application of landscape development models under changing climatic conditions is being addressed within the framework of MODARIA Working Group 6, so it is not considered further here.

k) An important issue to be addressed is the integration of the various modelling tools to address situations in which complex, non-linear feedbacks arise, e.g. in the context of the development of permafrost. In the context of modelling ground freezing, changes in hydrogeology and solute expulsion, there is already modelling experience available, so no fundamental issues appear to arise. A less well developed area is the integration of models of biogeochemical cycling into a wider hydrogeological and hydrogeochemical context. Here, one of the issues is that organic materials are typically heterogeneous and poorly characterised chemically. Therefore, including organic materials directly into a general geochemical modelling tool is unlikely to be a viable option. Indeed, it may be more sensible to approach this issue through specific consideration of a limited number of radionuclides of particular importance in performance assessments, e.g. C-14, Cl-36, Se-79 and I-129, so that well posed questions can be developed relating to the geochemical and biological processes controlling their transport and distribution in the GBI (defined to include both surface soils and the associated vegetation).

l) It is clear that integration of modelling tools can be facilitated through the use of platforms such as COMSOL Multiphysics and this is an area deserving of intense effort over the next few years. An important start has been made in this area by Amphos21 and this provides a good basis for such further developments. A potential way forward is to use the methodology set out in Section 3 to develop conceptual models for GBIs of interest and then to investigate how those conceptual models could be implemented using existing mathematical modelling tools or adaptations of them within a platform such as COMSOL Multiphysics.

m) Where possible, validating models using simple systems should be carried out. There may be more examples that could be explored to improve confidence in some of the more complex models, and this may be important for communicating model concepts.

6.5 ROLE OF MODELS OF THE GEOSPHERE-BIOSPHERE INTERFACE IN ASSESSMENTS

n) Models of the GBI need to be representative; with regard to this, identifying where or what the weakest link in the model might be is significant. This may be defined as 'what is not genuinely representative'.

o) Models of the GBI may need to go one step beyond what is required for assessment purposes. It will then be possible to develop simplified, abstracted models for use in the assessment. However, this requirement of going one step too far in order to demonstrate the robustness of the simplified assessment approach must be balanced by ensuring that undue resources are not expended in exploring secondary issues in excessive depth.

6.6 RECOMMENDATIONS FOR FUTURE WORK

Based on the work described in earlier sections of this report and the discussions that took place at the second workshop [BIOPROTA, 2014], the following objectives for future work were made by the participants.

p) A study should be undertaken to explore priorities for focusing on specific radionuclides of common interest to long-term safety assessment.

q) The concept of a natural or anthropogenically modified natural test system as a means to facilitate engagement with specialists in other disciplines should be developed. The mire or other wetland domain was chosen as a potential candidate, since this was of interest to the majority of participants, is a particularly fruitful context in which to explore relationships between hydrological, hydrochemical and biological processes, and is also of interest to BIOPROTA participants with a specific interest in C-14 and who are involved in ongoing BIOPROTA co-ordinated work on this radionuclide.

More generally, the work described in this report could be developed by applying the methodology described in Section 3 to develop the existing examples further or to generate conceptual models for additional situations of interest. In either case, the next stage would be to investigate how those conceptual models could be implemented using existing mathematical modelling tools or adaptations of them within a platform such as COMSOL Multiphysics.

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APPENDIX A: CHARACTERISTICS OF THE GEOSPHERE-BIOSPHERE INTERFACE IN PREVIOUS ASSESSMENTS

A.1 THE GENERIC DISPOSAL SYSTEM SAFETY CASE DEVELOPED BY RWMD

A.1.1 Assessment Context

The Nuclear Decommissioning Authority (NDA) has established the Radioactive Waste Management Directorate (RWMD) to manage the delivery of geological disposal for higher activity radioactive wastes, as required under UK Government policy published in the Managing Radioactive Waste Safely (MRWS) White Paper [Defra *et al*., 2008]. This policy also states that the siting of a geological disposal facility (GDF) will be based on a voluntarism and partnership approach.

The definition of geological disposal given by the UK Government's advisory Committee on Radioactive Waste Management (CoRWM) in its recommendations to UK Government in 2006 [CoRWM, 2006] has been followed through in the UK Government response to those recommendations [UK Government, 2006] and in the MRWS White Paper. This is 'burial underground (200 - 1,000m) of radioactive waste in a purpose-built facility with no intention to retrieve …'.

The MRWS White Paper provides an estimate - the 'Baseline Inventory' - of the higher activity radioactive waste and other materials that could, possibly, come to be regarded as wastes that might need to be managed in the future through geological disposal. The Baseline Inventory is based on the 2007 UK Radioactive Waste Inventory (UKRWI) [NDA and Defra, 2008]. It includes materials not currently classified as waste - spent nuclear fuel, and separated plutonium and uranium stocks. However, it excludes low level radioactive waste (LLW) that can be managed under the Government's 'Policy for the Long Term Management of Solid Low Level Radioactive Waste in the United Kingdom'. [Defra *et al*., 2007].

For planning purposes, the Baseline Inventory is used as the basis for developing a disposal system specification [NDA, 2010b; 2010c] and, in turn, GDF engineering designs [NDA, 2010d] that meet this specification. These facility designs provide the basis for assessments of the associated safety and environmental, social and economic impacts and for assessments of costs.

The MRWS White Paper sets out the Baseline Inventory in terms of volume and activity, as shown in Table A.1, according to waste category, and recognises the figures are only indicative. For design and assessment purposes, more detailed information related to waste packages is needed and, therefore, a more detailed inventory based upon the Baseline Inventory and using the information from the 2007 UK RWI has been developed. The term 'Derived Inventory' is used to explain this, but in the first instance this should be seen as a more detailed description of the Baseline Inventory.

Materials	Packaged volume		Radioactivity (At 1 April 2040)	
	Cubic Metres	%	**Terabequerels**	%
HLW	1,400	0.3%	36,000,000	41.3%
ILW	364,000	76.3%	2,200,000	2.5%
LLW (not for LLWR)	17,000	3.6%	<100	0.0%
Spent nuclear fuel	11,200	2.3%	45,000,000	51.6%
Plutonium	3,300	0.7%	4,000,000	4.6%
Uranium	80,000	16.8%	3,000	0.0%
Total	**476,900**	**100**	**87,200,000**	**100**
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Table A.1: The MRWS White Paper Baseline Inventory

A.1.2 Geological Characteristics of the Generic Environments under Consideration

At the current stage of the MRWS process, no site-specific studies are being undertaken. Thus, only generic alternative geological contexts are being modelled in assessment studies. Work that was carried out in 2008 identified a range of possible concepts for geological disposal of intermediate-level and low-level radioactive waste (ILW/LLW) [Hicks *et al*., 2008], and of high-level radioactive waste (HLW) and spent fuel (SF) [Baldwin *et al*., 2008], effectively providing a catalogue of concepts for consideration. The work drew on previous work in the UK, and disposal programmes in other countries, to identify disposal concepts for generic geological settings (host rock formations and associated geological and hydrogeological conditions).

At the current stage of the programme RWMD is examining a wide range of potentially suitable disposal concepts so that a well-informed assessment of options can be carried out at appropriate decision points in the implementation programme. Drawing from this work, illustrative concepts for three generic geological settings have been set out, including the associated variants on rock formations that might overlie the GDF host rock.

RWMD is using these illustrative concepts to:

- further develop understanding of the functional and technical requirements of the disposal system;
- further develop understanding of the design requirements;
- support the scoping and assessment of the safety, environmental, social and economic impacts of a GDF;
- support development and prioritisation of a research and development programme;
- underpin an analysis of the potential cost of geological disposal;
- support assessment of the disposability of waste packages proposed by waste owners.

RWMD has set out the illustrative concepts solely for these purposes. It is not intended that one of these illustrative concepts is necessarily the one that would be used in the relevant geological setting. At this stage, no geological disposal concept has been ruled out. However, the selected concepts are well-developed and supported by extensive research and development, and have been subject to detailed safety assessment, regulatory scrutiny and international review [Nirex, 2005].

The illustrative concepts are listed in Table A.2 and the attached notes present the key reasons why these examples were selected.

Host rock	Illustrative Geological Disposal Concept Examples[d]	
	ILW/LLW	HLW/SF
Higher strength rocks[a]	UK ILW/LLW Concept *(NDA, UK)*	KBS-3V Concept *(SKB, Sweden)*
Lower strength sedimentary rock[b]	Opalinus Clay Concept *(Nagra, Switzerland)*	Opalinus Clay Concept *(Nagra, Switzerland)*
Evaporites[c]	WIPP Bedded Salt Concept *(US-DOE, USA)*	Gorleben Salt Dome Concept *(DBE-Technology, Germany)*

Notes

a. Higher strength rocks – the UK ILW/LLW concept and KBS-3V concept for spent fuel were selected due to availability of information on these concepts for the UK context.

b. Lower strength sedimentary rocks – the Opalinus Clay concept for disposal of long-lived ILW, HLW and spent fuel was selected because a recent OECD Nuclear Energy Agency review regarded the Nagra (Switzerland) assessment of the concept as state of the art with respect to the level of knowledge available. However, it should be noted that there is similarly extensive information available for a concept that has been developed for implementation in Callovo-Oxfordian Clay by Andra (France), and which has also been accorded strong endorsement from international peer review. Although we will use the Opalinus Clay concept as the basis of the illustrative example, we will also draw on information from the Andra programme. In addition, we will draw on information from the Belgian super container concept, based on disposal of HLW and spent fuel in Boom Clay.

c. Evaporites – the concept for the disposal of transuranic wastes (TRU) (long-lived ILW) in a bedded salt host rock at the Waste Isolation Pilot Plant (WIPP) in New Mexico was selected because of the wealth of information available from this United States Environmental Protection Agency (EPA) certified, and operating facility. The concept for disposal of HLW and spent fuel in a salt dome host rock developed by DBE Technology (Germany) was selected due to the level of concept information available.

d. For planning purposes the illustrative concept for depleted, natural and low enriched uranium is assumed to be same as for ILW/LLW and for plutonium and highly enriched uranium is assumed to the same as for HLW/SF.

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Table A.2: Illustrative Geological Disposal Concept Examples for different Waste Types

The use of generic geological settings does not imply that any specific sites are being considered. The host rock descriptions correspond to three distinct general rock types that are considered potentially suitable to host a disposal facility for higher activity wastes, based on studies carried out in the UK and internationally, and which occur in the UK. They are described as follows.

- Higher strength rocks - these would typically comprise crystalline igneous, metamorphic rocks or geologically older sedimentary rocks, where any fluid movement is predominantly through divisions in the rock, often referred to as discontinuities. Granite is a good example of a rock that would fall in this category.
- Lower strength sedimentary rocks - these would typically comprise geologically younger sedimentary rocks where any fluid movement is predominantly through the rock mass itself. Many types of clay are good examples of this category of rocks.
- Evaporites - these would typically comprise anhydrite (anhydrous calcium sulphate), halite (rock salt) or other evaporites that result from the evaporation of water from water bodies containing dissolved salts.

A.1.3 The Geosphere-Biosphere Interface

In defining the types of future biosphere systems of interest for assessment purposes, RWMD concentrates on climate change, together with future human actions, as the major factors that determine biosphere change [Thorne and Kane, 2006; NDA, 2010e].

Various landscape evolution scenarios have been developed for the British Isles, focusing on lowland landscapes. The emphasis has been on inland landscapes for two reasons. First, impacts of releases to terrestrial environments are orders of magnitude larger than impacts of the same releases to estuarine or marine environments, due to the much larger degree of initial dilution occurring in the latter contexts. Secondly, assessments of impacts in shoreline environments would depend on details of the characteristics of both the geosphere and biosphere and cannot readily be evaluated in a generic context. Thus, consideration of radiological impacts in coastal environments has been deferred for future consideration, as required [NDA, 2010e]. However, in the interim RWMD has extended the scope of its post-closure biosphere assessment model to encompass generic coastal (estuarine and open shoreline) and marine (near-shore and offshore) environments representative of the UK [Walke *et al.*, 2012a].

Illustrative patterns of landscape evolution [NDA, 2010e] are shown in Figures A.1 and A.2.

Period	Illustration	State & Notes
0 to 50 ka		**Temperate:** Predominantly agricultural; denudation reduces relief slowly over time; long-term isostatic adjustment.
50 to 100 ka		**Boreal:** Incision in the upper catchment; aggregation of coarser deposits in the valley floor; continued isostatic adjustment.
100 to 105 ka		**Periglacial/glacial:** Further incision and aggregation of coarser sediments; continued isostatic adjustment; unlikely to be permanent human occupancy under full glacial conditions, though there would be likely to be extensive hunting and herding activities under periglacial conditions.
105 to 115 ka		**Boreal:** Further incision in the upper catchment and aggregation of coarser deposits in the valley floor; continued isostatic adjustment.
115 to 140 ka		**Temperate:** Return to gradual denudation; finer sediments accumulate over the coarser deposits in the valley floor; gradual increase in catchment size.

Figure A.1: Future Landscape Development for a Medium-sized Catchment under a Climate Evolution Scenario with no Fossil Fuel Contribution [from NDA, 2010e]

Period	Illustration	State & Notes
0 to 170 ka		**Sub-tropical:** Susceptible to erosion, but stable under good land management; long period of erosion and aggregation of fine sediments in the valley bottom progressively reduces relief; water is scarce and managed for farming, including irrigation.
170 to 200 ka		**Temperate:** Catchment relief may have been reduced by half by this time; fertile soils in the valley floors intensively farmed.

Figure A.2: Future Landscape Development with a Passive Catchment Response under a Climate Evolution Scenario with a Fossil Fuel Contribution leading to Warmer Conditions over the next 200,000 years [from NDA, 2010e]

With respect to the spatially distributed modelling of surface-water catchments, although RWMD has investigated the capabilities of both the SHETRAN and MIKE SHE/MIKE11 systems [NDA, 2010e], the current situation is that further work is being undertaken to compare the capabilities of these systems to determine if and how these tools should be used in support of future assessment studies. It is possible that both tools will be used for different purposes, and/or that work will be put in hand 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 [NDA, 2010e]. However, in the most recent assessments that have been undertaken by RWMD, spatially distributed modelling has not been used and a much simpler characterisation of the GBI has been adopted. Furthermore, the emphasis has been on modelling future sub-tropical, temperate and boreal conditions, which have the potential to persist for 100 to 200 ka in Britain (Figures A.1 and A.2), which is a long enough period for significant releases of radionuclides to occur from a GDF to the surface environment, at least in some of the geological contexts of interest.

Under these climatic conditions, and in the context of Lowland Britain, agriculture is likely to be practiced extensively. Thus, the Potentially Exposed Groups (PEGs) that are considered make extensive use of local resources through smallholding or farming. Because of the emphasis on agricultural contexts that are likely to predominate in lowland Britain, only limited consideration to is given to exposure due to consumption of wild foods. However, as this pathway is more relevant in other climatic conditions, RWMD continues to keep it under review.

The main focus of RWMD biosphere assessment calculations has been on specific biosphere states, rather than on the transitions between them. Furthermore, because of the long period of interglacial conditions that RWMD projects to occur and because land use is particularly intense under such conditions, the main applications of our biosphere assessment model to date have related to a situation in which intensive crop and animal production is practised in a temperate environment.

The biosphere model itself relates only to radionuclide transport in the soil zone, including subsequent leaching of activity in the subsoil and topsoil to a local stream or river, and abstraction of contaminated water from a shallow well, with that water being used subsequently for a variety of domestic purposes, as well as for irrigation of plants and as drinking water for animals. Radionuclides enter the soil zone either in upwelling groundwater or in irrigation water.

Although, 2D and 3D groundwater flow and radionuclide transport calculations can be undertaken, in practice, the geosphere model used for assessment studies delivers radionuclide fluxes to the biosphere model (expressed as Bq a^{-1}). However, the biosphere model requires the upwardly directed flux per unit area (Bq m^{-2} a^{-1}) for groundwater discharging to the soil zone and the concentration in well water (Bq m^{-3}) for the well abstraction pathway. The conversions are achieved by dividing the delivered flux by the discharge area, A (m^2), or by the flow rate in the near-surface aquifer, F (m^3 a^{-1}) [See Appendix B of NDA, 2010e].

Although the biosphere assessment model has been implemented such that transient calculations can be undertaken using time-dependent fluxes of radionuclides from the geosphere, in practice calculations are undertaken for unit values of flux per unit area or unit concentrations in well water occurring over periods that are long enough for equilibrium to be established. Thus, the model is used to derive Biosphere Dose Conversion Factors (BDCFs) for the groundwater discharge and well abstraction pathways, $BDCF_{gw}$ and $BDCF_{well}$ with units of Sv a^{-1} per Bq m^{-2} a^{-1} and Sv a^{-1} per Bq m^{-3}, respectively. An overall BDCF factor is also defined, $BDCF_{total}$ that applies to unit flux from the geosphere assuming that it both contaminates the local aquifer and results in local discharge to agricultural soils. The units of $BDCF_{total}$ are Sv a^{-1} per Bq a^{-1}. The relationship between these quantities is:

$$BDCF_{total} = BDCF_{gw}/A + BDCF_{well}/F$$

The selection of appropriate values of F and A has recently been discussed [Walke *et al*., 2012b].

A typical value for the flow rate, F, can be estimated by considering both the potential flow through a near-surface aquifer and the demands that might be placed upon it. For these calculations, the lateral extent of the GDF perpendicular to the aquifer flow direction is taken to be 500 m and it is assumed that negligible lateral dispersion of the radionuclide plume occurs during transport from the repository to the near-surface aquifer. Assuming that the saturated thickness of the aquifer is 10 m (as might occur for an aquifer developed in near-surface weathered rock or in overlying Quaternary sediments), then the relevant area of flow is around 5,000 m^2. The uncertainty in this area is relatively small compared with the uncertainty in the flow rate within the aquifer. Taking an unsaturated hydraulic conductivity in the range 3 10^{-4} to 1 10^{-5} m s^{-1} (appropriate to unconsolidated sand through to weathered bedrock) and an average hydraulic gradient of around 0.01 (appropriate to lowland areas with average ground slopes of this order of magnitude), the flow rate is in the range from 3 to 100 m^3 m^{-2} a^{-1}. Thus, F is in the range 1.5 10^4 to 5 10^5 m^3 a^{-1}.

The value of F is used primarily in calculating radionuclide concentrations in well water. An unlicensed domestic well, supporting a household with a water demand of 2 m^3 d^{-1} (5 people at the reasonably high water demand of 0.4 m^3 d^{-1} per head) would require abstraction at a rate of about 730 m^3 a^{-1}. This would be only a small perturbation even at an aquifer flow rate of only 1.5 10^4 m^3 a^{-1}. If the well were to also be used for irrigation of smallholdings or vegetable gardens and as a source of drinking water to farm animals, these also need to be considered. For example, if the household has a garden area of 500 m^2 used for growing vegetables (to supply the household) with an irrigation rate of 0.1 m a^{-1}, this would imply an additional rate of use of water of 50 m^3 a^{-1}. If the smallholding has 5 cows which drink 0.4 m^3 d^{-1} this will add another 730 m^3 a^{-1} to the water demand. The total water demand for the unlicensed well would therefore be ~ 1560 m^3 a^{-1}. Again, this is only a small perturbation of the minimum aquifer flow rate calculated above. Note that it is assumed the well water would not be used for irrigating pasture in the current UK climate, or even in moderately greenhouse-warmed conditions, though it might be so used in an extreme Mediterranean to sub-tropical environment. A licensed domestic well would likely have a flow rate about an order of magnitude larger, i.e. about 20 m^3 d^{-1} or 7,300 m^3 a^{-1}, which would not perturb a value of mixing flow, *F*, of 5 10^5 m^3 a^{-1} which could therefore be an upper bounding value for this type of well.

In summary, Walke *et al.* [2012b] concluded that it seems reasonable to use a range of values of *F* of 1.5 10^4 to 5 10^5 m^3 a^{-1}. A rounded geometric mean value would be 1 10^5 m^3 a^{-1}. Walke *et al*. [2012b] note that in previous studies, e.g. Thorne [2008], a reference value of 3 10^5 m^3 a^{-1} was adopted.

With respect to the discharge area, *A*, Walke *et al*. [2012b] noted that small surface-water catchments typically have an area of a few square kilometres. This sets an upper bound on the area that might be adopted. However, the discharge might be primarily to riparian areas adjacent to a stream or river. For a width of the riparian zone of a few tens of metres and a length of 500 m (based on the lateral extent of the radionuclide plume) the area is ~ 1 to 2 hectares. This is large enough to support a smallholding, but with only limited grazing for cattle. Also, the water flow through this area would include a component from upslope. This is not accounted for in the model, but would tend to reduce radionuclide concentrations in the subsoil and topsoil. In view of these considerations, Walke *et al*. [2012b] considered that it seems reasonable to adopt a value of *A* in the range 2 10^4 to 1 10^7 m^2. The geometric mean of this range is 4 10^5 m^2. Assuming that the hydrologically effective rainfall in lowland Britain is around 0.3 m, this gives a stream flow rate for the catchment of only 1.2 10^5 m^3 a^{-1} (0.004 m^3 s^{-1}). This represents a small, and possibly ephemeral, stream, so it would not be appropriate to include human or animal drinking water pathways, or foliar irrigation, for a discharge area this small. Thus, if all pathways are to be included in the model, the discharge area must necessarily be larger. This leads to a more limited range for *A* of 1 10^6 to 1 10^7 m^2, with a typical value of 3 10^6 m^2. In previous studies, a reference value of 1 10^7 m^2 was used [Thorne, 2008].

A.2 THE LICENSE APPLICATION FOR YUCCA MOUNTAIN

A.2.1 Assessment Context

The programme for site characterisation and safety assessment of Yucca Mountain, Nevada as a potential location for geological disposal of SF and HLW has its origins in the US Nuclear Waste Policy Act (NWPA) of 1982, which marked the beginning of a new chapter in US efforts to deal with the nuclear waste issue. The legislation was the product of four years of Congressional debate marked, on the one hand, by growing concern about an imminent shortage of spent-fuel storage pool capacity at operating reactors and, on the other hand, by an equally urgent concern on the part of individual states that they not be selected to host a repository site [Blue Ribbon Commission on America's Nuclear Future, 2012].

Recognising the need for a Congressional mandate to overcome opposition to the selection of any given site, Congress sought through the NWPA to establish a fair and technically sound process for selecting repository locations. In fact, to avoid the perception that any one state or locale would be asked to bear the entire burden of the national nuclear waste management obligations, the Act provided for the selection of two repository sites (though not stipulated in the legislation itself, it was widely assumed that one of these sites would be located in the West, the other in the East). To further ensure that the end result would not be a single, national repository, Congress included provisions explicitly limiting the capacity of the first repository to 70,000 metric tons until a second repository was opened [Blue Ribbon Commission on America's Nuclear Future, 2012].

In May 1986, the Energy Secretary recommended the Hanford site in Washington State, Deaf Smith County in Texas, and Yucca Mountain, Nevada for detailed site characterisation as leading candidates for the first permanent high-level geologic waste repository.

By that time, however, DOE's efforts to identify promising sites, not only for the two permanent repositories but also for a monitored retrievable storage (MRS) facility, were drawing strong opposition from the elected officials of all potentially affected states. Citing rising costs and lower projections for nuclear waste production in the future, the Energy Secretary announced that DOE was suspending efforts to identify and develop a second permanent geologic repository. This announcement, in May 1986, served to intensify the opposition of the three states that had been selected as potential hosts for the first repository.

Faced with a deteriorating political situation and growing recognition that the original timelines and cost assumptions set out in the NWPA were unrealistic, Congress revisited the issue of nuclear waste management in 1987. The resulting NWPA Amendments Act of 1987 halted then ongoing research in crystalline rock of the type found in the Midwest and along the Atlantic coast, cancelled the second repository programme, nullified the selection of Oak Ridge, Tennessee as a potential MRS site, and designated Yucca Mountain as the sole site to be considered for a permanent geologic repository [Blue Ribbon Commission on America's Nuclear Future, 2012].

Following the dictates of the 1987 NWPA Amendments, DOE continued detailed site characterisation studies at Yucca Mountain through the 1990s and issued a formal finding on the suitability of the site in 2002, which was four years past the 1998 deadline by which the federal government was obliged to begin accepting commercial nuclear waste for disposal under the NWPA. The President's subsequent recommendation of the site to Congress prompted Nevada, which had remained staunchly opposed to the project throughout, to file an official "Notice of Disapproval". However, a Congressional resolution to override the state's veto was signed by the President, clearing the way for DOE to apply to the NRC for a license to commence construction. The latter step was supposed to follow fairly quickly (within 90 days), but due to litigation over the repository safety standards, persistent funding shortfalls, and other problems it took another six years before the application for construction authorization was filed with the NRC.

In the end, DOE succeeded in completing the world's first license application for a HLW repository. Submitted to the NRC in June 2008, the license application was deemed suitable for review three months later. Within a year, however, the new Administration declared its intent to suspend further work on Yucca Mountain and later moved to withdraw the application for a construction license to the NRC. At this point, with key decisions by the courts and the NRC still pending, the future of the Yucca Mountain project remains uncertain.

A.2.2 Geological Context of the Proposed Repository at Yucca Mountain

To understand the hydrogeology of Yucca Mountain, it has to be appreciated that that the superficial strata comprise a sequence of volcanic tuffs. These overlie thick carbonate rocks that form a deep regional aquifer within the groundwater flow system. At Yucca Mountain, the unsaturated zone, which extends to a depth of several hundred metres and within which the proposed repository would be located, comprises a sequence of welded and nonwelded tuffs. Whereas the welded tuffs are heavily fractured, the nonwelded tuffs are less fractured, so the hydrogeological models that have been developed tend to emphasise fracture flow in the welded tuffs and matrix flow in the unwelded tuffs. This is a gross simplification, as Table 1 of Chapter 2 of Stuckless [2012] illustrates, formations like the Paintbrush (PTn), that are broadly described as nonwelded, include moderately welded subzones. Furthermore, fracturing can extend across multiple welded and nonwelded layers. Connected fractures can extend from the surface to repository depth and below. These may constitute fast pathways for water flow. Evidence for such pathways has been obtained from measurements of ratios of bomb-pulse ^{36}Cl to stable chloride at the proposed repository level.

Radionuclides released from the repository would travel downward through the unsaturated zone until they reached the water table. Within the Yucca Mountain area, groundwater primarily flows south through the sequence of volcanic rocks and the underlying carbonate aquifer. Limited available data suggest that groundwater heads are generally higher in the regional carbonate aquifer than in the overlying volcanic strata. This indicates that any radionuclide releases from the proposed repository would be expected to be mainly restricted to the volcanic system [Stuckless, 2012; Chapter 3, page 123], though it is difficult to entirely rule out leakage to the carbonate aquifer given the hydrogeological complexity of the environment. Where the volcanic rocks pinch out to the south of Yucca Mountain, the groundwater flow passes from the volcanic rocks to Tertiary alluvial and carbonate deposits [Stuckless, 2012; Chapter 3, page 112]. Thus, for pathlines originating from below the location of the proposed repository, the first part of the pathline is associated with flow in fractures, whereas the second part is associated with flow in alluvial material that can be appropriately modelled as an inhomogeneous continuous medium.

With respect to radionuclide transport, the same conceptual model that has been adopted by all parties in radiological impact assessment studies of the proposed disposal facility. Radionuclides leaking downward from the repository enter the saturated zone mainly within the repository footprint. From there they move south in a narrow plume, initially within the volcanic aquifer, but then in the Tertiary alluvium. Well extraction occurs from the alluvium and is used for crop irrigation and domestic purposes in the southern part of the Amargosa Desert (often referred to as the Amargosa Valley).

A summary description of the characteristics of the alluvial aquifer is provided in Annex 1.

A.2.3 Regulatory Considerations determining the Geosphere-Biosphere Interface

The GBI at Yucca Mountain is constrained by the prescriptive regulatory regime that is applicable. The relevant regulation is Code of Federal Regulations 10 CFR 63, which relies, in turn upon 40 CFR 197. All quotations given below are taken from the 2012 consolidated edition of the Code of Federal Regulations. Note that § signifies a cross reference to another section of the same part of the Code of Federal Regulations.

40 CFR 197.15 requires that:

> The DOE should not project changes in society, the biosphere (other than climate), human biology, or increases or decreases of human knowledge or technology. In all analyses done to demonstrate compliance with this part, DOE must assume that all of those factors remain constant as they are at the time of license application submission to NRC. However, DOE must vary factors related to the geology, hydrology, and climate based upon cautious, but reasonable assumptions of the changes in these factors that could affect the Yucca Mountain disposal system during the period of geologic stability, consistent with the requirements for performance assessments specified at § 197.36.

40 CFR 197.20 requires that:

> (a) The DOE must demonstrate, using performance assessment, that there is a reasonable expectation that the reasonably maximally exposed individual receives no more than the following annual committed effective dose equivalent from releases from the undisturbed Yucca Mountain disposal system: (1) 150 microsieverts (15 millirems) for 10,000 years following

disposal; and (2) 1 millisievert (100 millirems) after 10,000 years, but within the period of geologic stability.

(b) The DOE's performance assessment must include all potential pathways of radionuclide transport and exposure.

The reasonably maximally exposed individual (RMEI) is defined at 40 CFR 197.21:

The reasonably maximally exposed individual is a hypothetical person who meets the following criteria: (a) Lives in the accessible environment above the highest concentration of radionuclides in the plume of contamination; (b) Has a diet and living style representative of the people who now reside in the Town of Amargosa Valley, Nevada. The DOE must use projections based upon surveys of the people residing in the Town of Amargosa Valley, Nevada, to determine their current diets and living styles and use the mean values of these factors in the assessments conducted for §§ 197.20 and 197.25; and (c) Drinks 2 liters of water per day from wells drilled into the ground water at the location specified in paragraph (a) of this section.

Although only drinking water consumption is listed, the requirement under 40 CFR 197.20(b) means that other uses of the abstracted well water, including irrigation of plants and use as animal drinking water must be addressed.

40 CFR 197 also addresses compliance with the groundwater protection standard, which is distinct from the protection standard applied to the RMEI and discussed above.

40 CFR 197.30 requires that:

The DOE must demonstrate that there is a reasonable expectation that, for 10,000 years of undisturbed performance after disposal, releases of radionuclides from waste in the Yucca Mountain disposal system into the accessible environment will not cause the level of radioactivity in the representative volume of ground water to exceed the limits in the following Table 1...

Table 1 is not reproduced here, because the specific numerical limits are not relevant in the current context. However, the definition of the representative volume of ground water is relevant. This is given in 40 CFR 197.31:

(a) It is the volume of ground water that would be withdrawn annually from an aquifer containing less than 10,000 milligrams of total dissolved solids per liter of water to supply a given water demand. The DOE must project the concentration of radionuclides released from the Yucca Mountain disposal system that will be in the representative volume. The DOE must then use the projected concentrations to demonstrate a reasonable expectation to NRC that the Yucca Mountain disposal system complies with § 197.30. The DOE must make the following assumptions concerning the representative volume: (1) It includes the highest concentration level in the plume of contamination in the accessible environment; (2) Its position and dimensions in the aquifer are determined using average hydrologic characteristics which have cautious, but reasonable, values representative of the aquifers along the radionuclide migration path from the Yucca Mountain repository to the accessible environment as determined by site characterization; and (3) It contains 3,000 acre-feet of water (about 3,714,450,000 liters or 977,486,000 gallons).

(b) The DOE must use one of two alternative methods for determining the dimensions of the representative volume. The DOE must propose its chosen method, and any underlying assumptions, to NRC for approval.

(1) The DOE may calculate the dimensions as a well-capture zone. If DOE uses this approach, it must assume that the: (i) Water supply well(s) has (have) characteristics consistent with public water supply wells in the Town of Amargosa Valley, Nevada, for example, well-bore size and length of the screened intervals; (ii) Screened interval(s) include(s) the highest concentration in the plume of contamination in the accessible environment; and (iii) Pumping rates and the placement of the well(s) must be set to produce an annual withdrawal equal to the representative volume and to tap the highest concentration within the plume of contamination.

(2) The DOE may calculate the dimensions as a slice of the plume. If DOE uses this approach, it must: (i) Propose to NRC, for its approval, where the location of the edge of the plume of contamination occurs. For example, the place where the concentration of radionuclides reaches 0.1% of the level of the highest concentration in the accessible environment; (ii) Assume that the slice of the plume is perpendicular to the prevalent direction of flow of the aquifer; and (iii) Assume that the volume of ground water contained within the slice of the plume equals the representative volume.

Similarly, 10 CFR 63.102(g) specifies that:

After permanent closure, the geologic repository is required to: (1) Limit radiological exposures to the reasonably maximally exposed individual, as specified at § 63.113(b); (2) Limit releases of radionuclides to the accessible environment to protect ground water, as specified at § 63.113(c); and (3) Limit radiological exposures to the reasonably maximally exposed individual in the event of human intrusion, as specified at § 63.113(d).

Human intrusion is not discussed further below. It involves intrusion into the repository and the associated perturbation to the groundwater pathway, but it does not affect the GBI defined for the RMEI or in relation to the groundwater standard.

10 CFR 63.102(i) reads as follows:

Reference biosphere and reasonably maximally exposed individual. The performance assessment will estimate the amount of radioactive material released to water or air at various locations and times in the future. To estimate the potential for future human exposures resulting from release of radioactive material from a geologic repository at Yucca Mountain, it is necessary to make certain assumptions about the location and characteristics of the reasonably maximally exposed individual. The environment inhabited by the reasonably maximally exposed individual, along with associated human exposure pathways and parameters, make up the reference biosphere, as described in § 63.305. The reasonably maximally exposed individual, as a hypothetical person living in a community with characteristics of the Town of Amargosa Valley, is a representative person using water with average concentrations of radionuclides as described at § 63.312. The reasonably maximally exposed individual is selected to represent those persons in the vicinity of Yucca Mountain who are reasonably expected to receive the greatest exposure to radioactive material released from a geologic repository at Yucca Mountain. Characteristics of the reference biosphere and the reasonably maximally exposed individual are to be based on current human behaviour and biospheric conditions in the region, as described in § 63.305 and § 63.312.

In addition, 10 CFR 102(n) addresses the separate groundwater protection standard:

> *Ground-water protection.* Separate ground-water protection standards are designed to protect the ground water resources in the vicinity of Yucca Mountain. These standards, specified at § 63.331, require the estimation of ground water concentrations in the representative volume of water. Depending on the radionuclide, the estimated concentrations must either be below a specified concentration or result in an annual, drinking water dose to the whole body or any organ of no greater than 0.04 mSv (4 mrem). Although the estimation of radionuclide concentrations in the representative volume would be a separate analysis, the analysis is similar to the performance assessment required by § 63.113(b) but subject to specific requirements for evaluation of ground-water protection specified at §§ 63.331, 63.332 and 63.342 of subpart L of this part.

The requirements for protection of groundwater are as set out in 40 CFR 197.31, reproduced above.

10 CFR 63.305 sets out the characteristics of the reference biosphere to be adopted:

> (a) Features, events, and processes that describe the reference biosphere must be consistent with present knowledge of the conditions in the region surrounding the Yucca Mountain site.
>
> (b) DOE should not project changes in society, the biosphere (other than climate), human biology, or increases or decreases of human knowledge or technology. In all analyses done to demonstrate compliance with this part, DOE must assume that all of those factors remain constant as they are at the time of submission of the license application.
>
> (c) DOE must vary factors related to the geology, hydrology, and climate based upon cautious, but reasonable assumptions of the changes in these factors that could affect the Yucca Mountain disposal system during the period of geologic stability, consistent with the requirements for performance assessments specified at § 63.342.
>
> (d) Biosphere pathways must be consistent with arid or semi-arid conditions.

10 CFR 63.112 then sets out the characteristics of the RMEI to be used within the framework of this reference biosphere:

> The reasonably maximally exposed individual is a hypothetical person who meets the following criteria:
>
> (a) Lives in the accessible environment above the highest concentration of radionuclides in the plume of contamination;
>
> (b) Has a diet and living style representative of the people who now reside in the Town of Amargosa Valley, Nevada. DOE must use projections based upon surveys of the people residing in the Town of Amargosa Valley, Nevada, to determine their current diets and living styles and use the mean values of these factors in the assessments conducted for §§ 63.311 and 63.321;
>
> (c) Uses well water with average concentrations of radionuclides based on an annual water demand of 3000 acre feet;
>
> (d) Drinks 2 liters of water per day from wells drilled into the ground water at the location specified in paragraph (a) of this section; and

(e) Is an adult with metabolic and physiological considerations consistent with present knowledge of adults.

Although the exposures of individuals with other characteristics have to be addressed in the Environmental Impact Assessment (EIS) submitted with the License Application, in practice these are given much less consideration than impacts on the RMEI. The Final Environmental Impact Statement (FEIS) considers radionuclide impacts (doses) at the RMEI location, 18 km from the repository boundary, at 30 km from the repository, and at a discharge location, Franklin Lake Playa, 60 km from the repository. The radionuclide impacts calculated at 30 and 60 km are based on a scaling factor that is applied to the impact at the RMEI location. The scaling factor accounts only for expected dispersion of the contaminants in the plume in the alluvial aquifer. It does not address details of the behaviour of the plume at the discharge location. As pointed out by the State of Nevada [Nevada, 2008; NEV-NEPA-21[a]]:

> There is no consideration given to the chemical, physical, hydrologic and ecological processes that function at Franklin Lake Playa. Together, these processes can result in concentration of radionuclides in water, mineral precipitates, soils, and plants, and make some portion of the concentrated radionuclides available for redistribution in the environment by surface water flow and wind. These concentration and redistribution processes have the potential to result in higher radiological impacts to individuals accessing the contaminated areas than those arising to the RMEI, as the water use and habits of the latter are strongly constrained by regulation.

However, modelling of these processes has been addressed by the Electric Power Research Institute (EPRI) [see Smith and Kozak, 2011].

Thus, overall, the regulatory regime applicable at Yucca Mountain, effectively defines the GBI to be the zone of influence of a borehole drilled into the alluvial aquifer in Amargosa Valley under present-day, semi-arid conditions and capable of extracting 3000 acre-feet per year ($3.7\ 10^6\ m^3\ a^{-1}$) of water.

A.2.4 Approach to Assessment

As in the case of the RWMD approach described in Section A.2.1, the US DOE uses equilibrium Biosphere Dose Conversion Factors (BDCFs). The approach adopted is described in Section 2.3.10.1 of the License Application [US DOE, 2009].

> The biosphere model, known as the Environmental Radiation Model for Yucca Mountain Nevada (ERMYN), tracks the environmental transport of radionuclides that originate from the repository through the biosphere and calculates annual dose to the RMEI per unit of radionuclide concentration in groundwater or in surface soil mixed with volcanic tephra. The primary outputs of the biosphere model are biosphere dose conversion factors (BDCFs), equivalent to the annual dose from all potential exposure pathways that the RMEI would experience as a result of a unit concentration of a radionuclide in groundwater (Section 2.3.10.5.1) or in surface soil mixed with volcanic tephra (Section 2.3.10.5.2).The TSPA model combines the BDCFs with estimates of radionuclide concentrations in groundwater and

[a] The State of Nevada has organised its contentions relating to the US DOE License Application into various categories. One of these categories relates to issues arising under the US National Environmental Policy Act of 1969, as amended. NEV-NEPA-21 is the 21st contention in this category.

in surface soil mixed with volcanic tephra from the saturated zone transport abstraction models and the volcanic tephra redistribution model, respectively, at the location of the RMEI, to calculate the predicted annual total dose required to evaluate compliance with the individual protection standards in proposed 10 CFR 63.311 and proposed 10 CFR 63.321 (Sections 2.3.10.5.1.2 and 2.3.10.5.2.2). This quantity represents the incremental annual dose that the RMEI would receive as a result of radionuclide releases from the geologic repository at Yucca Mountain, in addition to, and exclusive of, the dose contributions from other sources, whether natural or man-made.

The calculations for surface soil mixed with volcanic tephra are only of relevance for releases due to extrusive igneous events (volcanism) and are not discussed further. The reference to the proposed 10 CFR 63 arises because this rule had not been finalised when the License Application was submitted. The TSPA is the probabilistic Total System Performance Assessment model used by the US DOE.

In the groundwater exposure scenario, the RMEI was taken to be exposed to the following six contaminated environmental media:

- Groundwater;
- Soil irrigated with groundwater;
- Indoor and outdoor air containing resuspended particles, radioactive gases, or aerosols from evaporative coolers;
- Crops irrigated with groundwater;
- Food products from animals fed with irrigated crops;
- Fish raised in groundwater at a fish farm.

The radionuclide concentration in groundwater for all exposure pathways included in the biosphere model that involved these media was calculated by dividing the annual mass flux of radionuclides (calculated in the geosphere component of the TSPA) by an annual water demand of 3,000 acre-feet, i.e. the concentration was based on the demand prescribed by regulation rather than by an explicit calculation of dilution in the volcanic/alluvial aquifer.

Because the biosphere model for the groundwater exposure scenario was based on unit concentrations of radionuclides in groundwater, there were few modelling approximations, assumptions, or methods used to model Features, Events and Processes (FEPs) that were shared with other TSPA model abstractions.

The conceptual and mathematical models for the groundwater exposure scenario were developed in the biosphere model as a series of eight sub-models. Figure A.3 shows the interactions among the sub-models. In addition to the eight sub-models, a separate sub-model was included to calculate ^{14}C concentrations in surface soil, air, crops, and animal products. This was done because carbon is a ubiquitous element and because some of the transfer mechanisms for ^{14}C would be different from the other radionuclides considered [see also SNL, 2007].

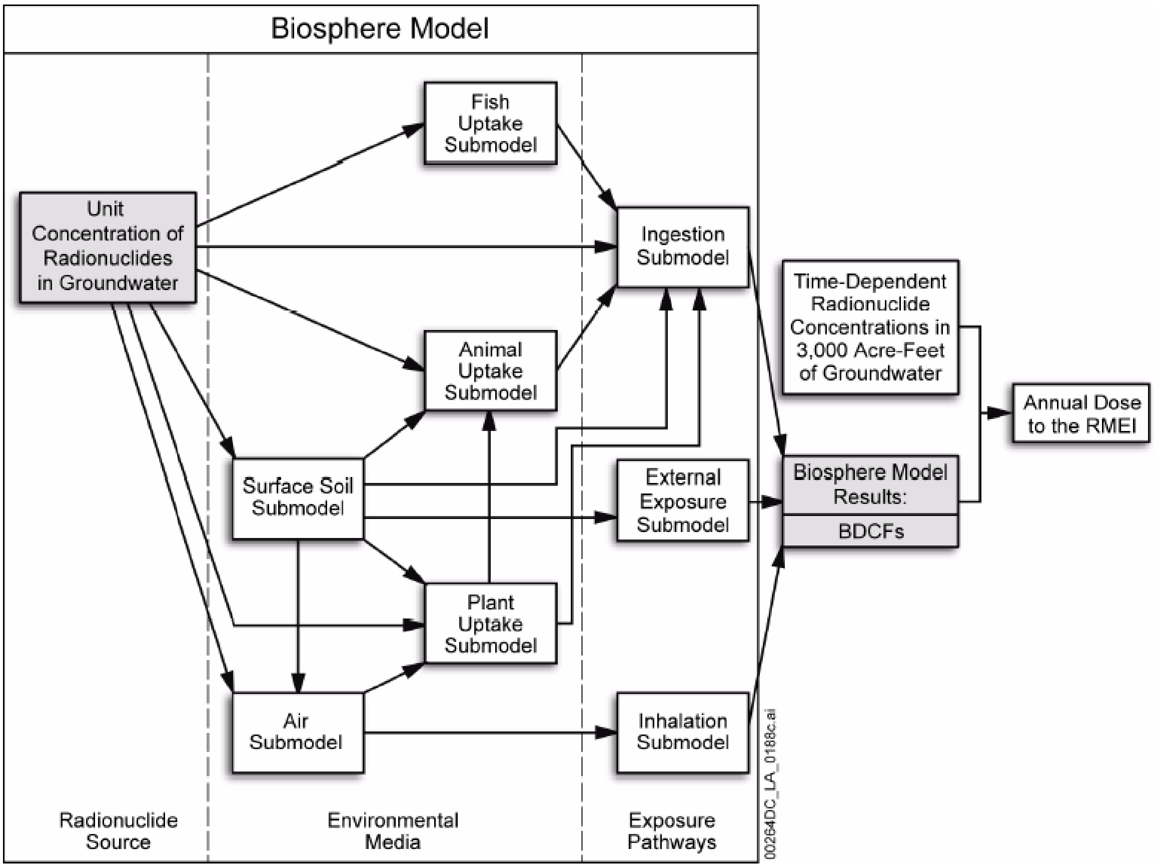


Figure A.3: Biosphere Sub-models included in ERMYN [Figure 2.3.10-9 of US DOE, 2009]

A.3 THE SAFETY CASE DEVELOPED BY SKB FOR A KBS3V REPOSITORY AT FORSMARK

A.3.1 Assessment Context

The most recent post-closure safety assessment conducted by SKB in relation to a KBS3-type repository for the deep geological disposal of SF is that included in the main report of the SR-Site project [SKB, 2011].

The SR-Site report is a main component in SKB's licence application to construct and operate a final repository for spent nuclear fuel at Forsmark in the municipality of Östhammar. Its role in the application is to demonstrate long-term safety for a repository at Forsmark.

Several decades of research and development has led SKB to put forward the KBS-3 method for the final stage of spent nuclear fuel management. In this method, copper canisters with a cast iron insert containing spent nuclear fuel are surrounded by bentonite clay and deposited at approximately 500 m depth in groundwater saturated, granitic rock; see Figure A.4. The purpose of the KBS-3 repository is to isolate the nuclear waste from man and the environment for very long times. Around 12,000 tonnes of spent nuclear fuel is forecasted to arise from the currently approved Swedish nuclear power programme (where the last of the 10 operating reactors is planned to end operation in 2045), corresponding to roughly 6,000 canisters in a KBS-3 repository.

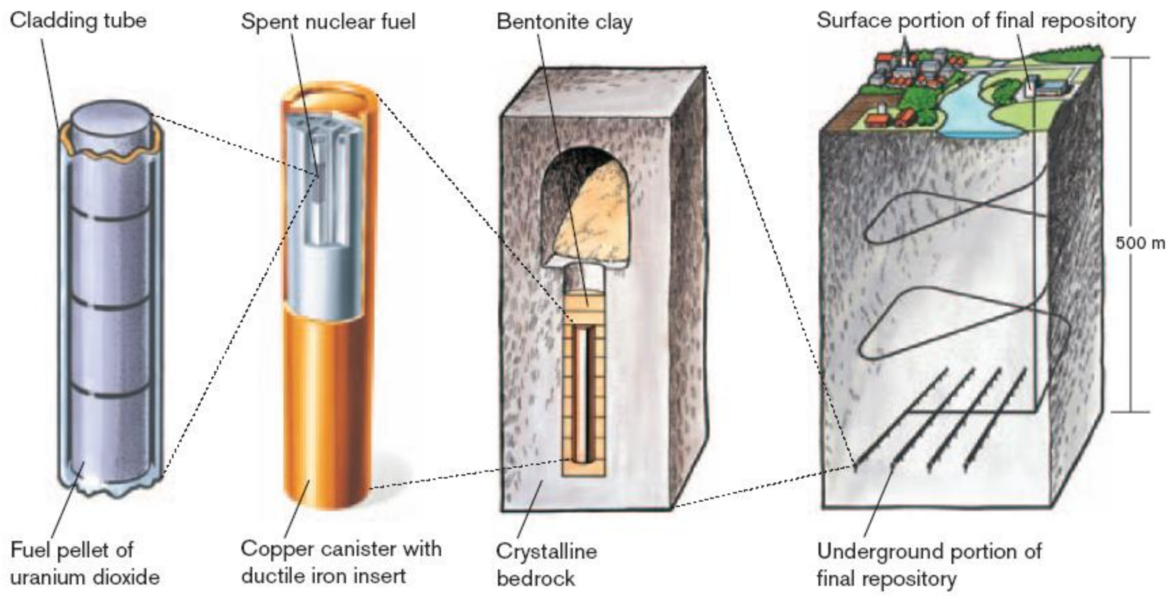


Figure A.4: The KBS-3V Concept for Disposal of Spent Fuel. Figure provided by SKB.

The regulations applicable in determining the safety of such a repository are:

The Swedish Radiation Safety Authority's regulations concerning safety in final disposal of nuclear waste (SSMFS 2008:21);

The Swedish Radiation Safety Authority's Regulations concerning the Protection of Human Health and the Environment in connection with the Final Management of Spent Nuclear Fuel or Nuclear Waste (SSMFS 2008:37).

The principal acceptance criterion, expressed in SSMFS 2008:37, concerns the protection of human health and requires that "the annual risk of harmful effects after closure does not exceed 10^{-6} for a representative individual in the group exposed to the greatest risk". "Harmful effects" refers to cancer and hereditary effects. The risk limit corresponds to an effective dose limit of about 1.4 10^{-5} Sv a^{-1}. Furthermore, the regulation SSMFS 2008:21 require descriptions of the evolution of the biosphere, geosphere and repository for selected scenarios; and evaluation of the environmental impact of the repository for selected scenarios, including the main scenario, with respect to defects in engineered barriers and other identified uncertainties.

In the General Guidance to SSM 2008:37, it is indicated that the time scale of a safety assessment for a final repository for spent nuclear fuel should be one million years after closure. A detailed risk analysis is required for the first thousand years after closure. Also, for the period up to approximately one hundred thousand years, the reporting is required to be based on a quantitative risk analysis.

For the period beyond one hundred thousand years, the General Guidance states that a strict quantitative comparison of calculated risk in relation to the criterion for individual risk in the regulations is not meaningful. Rather, it should be demonstrated that releases from both engineered and geological barriers are limited and delayed as far as reasonably possible using calculated risk as one of several indicators.

In the post-closure safety assessment, SKB argues that the vast majority of disposal canisters will retain their integrity over the full one million year assessment period. However, there are two variant scenarios for which canister failures cannot be excluded over this period. These are the corrosion scenario and the shear-load scenario.

Canister failure due to corrosion could occur for the case of advective transport of groundwater through an eroded buffer, with sulphide in the groundwater as the important corroding agent. Evaluating all the advective situations and other uncertainties related to corrosion led to a range of potential extents of corrosion failure. In the most pessimistic variants of this scenario, the first canister failures and hence the first releases occur after around 50,000 years. In these variants, the mean dose is about two orders of magnitude below the regulatory limit at 100,000 years and about one order of magnitude below the limit at one million years.

Canister failure due to shear load could arise as a result of earthquake-induced movements of faults. Risks of this scenario occurring would be minimised by adopting criteria to ensure that canisters were not disposed close to major deformation zones and that the deposition holes were not located intersecting or close to faults of above a specified size. Nevertheless, some failures due to shear load cannot be ruled out. For the shear load scenario, with pessimistically derived frequencies of canister failures, the calculated mean dose for the initial 1,000 years is negligible in comparison to the dose corresponding to the regulatory risk limit. Between 1,000 and 100,000 years, the calculated mean dose is about three orders of magnitude below the limit and then increases to become about two orders of magnitude below the limit at one million years.

In either the canister corrosion or shear-load scenarios, radionuclides are assumed to be relatively rapidly released from the waste containers and transported to the biosphere. Assessment calculations are undertaken for time-varying interglacial biosphere systems occurring far in the future (see Section A.3.3).

A.3.2 Geological Characteristics

The Forsmark site is located in northern part of the county of Uppland within the municipality of Östhammar, about 170 km north of Stockholm. The Forsmark area consists of crystalline bedrock that belongs to the Fennoscandian Shield and formed 1.85 to 1.89 billion years ago. Tectonic lenses, in which the bedrock is less affected by ductile deformation, are enclosed in between ductile high strain belts. The candidate area is located in the north-westernmost part of one of these tectonic lenses. This lens extends from north-west of the Forsmark nuclear power plant south-eastwards to the area around Öregrund (Figure A.5).

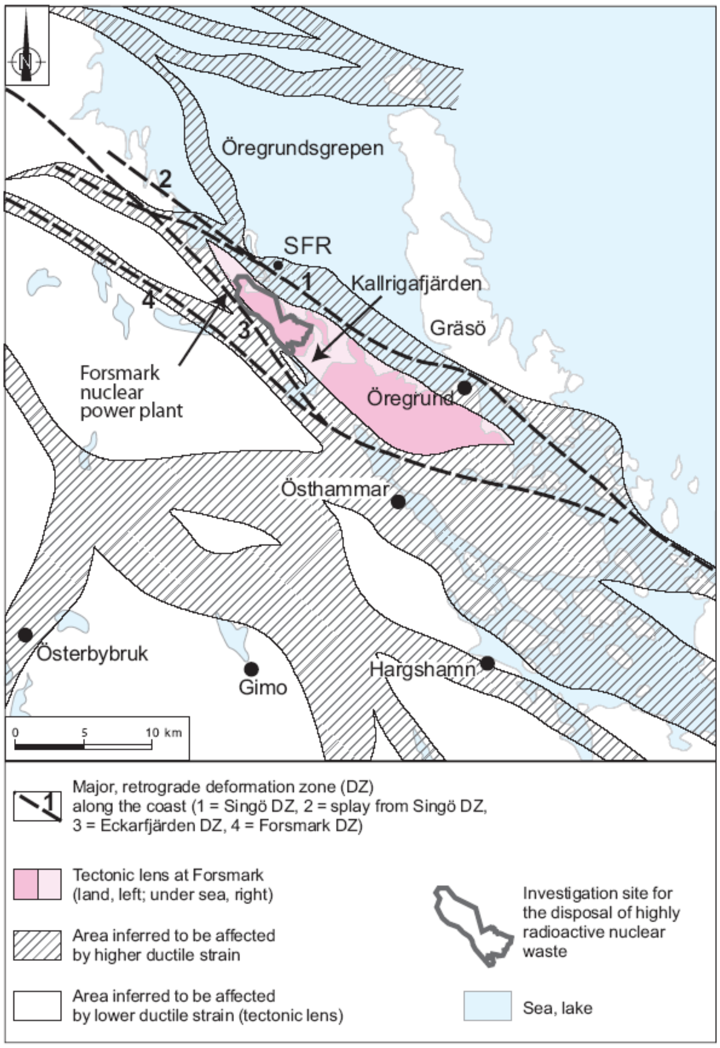


Figure A.5: Tectonic Lens at Forsmark and Areas affected by Strong Ductile Deformation in the Area close to Forsmark [SKB, 2011]. SFR is the existing near-surface facility for disposal of low-level and intermediate-level radioactive wastes.

Three major sets of deformation zones with distinctive orientations have been recognised. In addition to vertical and steeply dipping zones, there are also gently south-east- and south-dipping zones. These gently dipping zones are more frequent in the south-eastern part of the candidate volume and have higher hydraulic transmissivity than vertical and steeply dipping deformation zones at the site.

The frequency of open and partly open fractures is very low below approximately 300 m depth compared to what is observed in the upper part of the bedrock in the north-western part of the candidate volume, which is the target volume for the repository. In addition, the rock stresses are relatively high compared to typical values of the Swedish bedrock. The upper 100 to 150 m of the bedrock overlying the target volume contains many highly transmissive fractures in the horizontal plane and in good hydraulic contact over long distances, whereas at depth the rock has very low permeability with few transmissive fractures. At repository depth (c. 470 m) the average distance between transmissive fractures is more than 100 m.

Groundwaters in the uppermost 100 to 200 m of the bedrock display a wide range of chemical variability, with chloride concentrations in the range 200 to 5,000 mg/L suggesting influence of both brackish marine water and meteoric waters. At depths between 200 and 800 m, the salinity remains fairly constant (5,000–6,000 mg/L) and the water composition indicates remnants of water from the Littorina Sea that covered Forsmark between 9,500 and 5,000 years ago. At depths between 800 and 1,000 m, the salinity increases to higher values.

During an interglacial period, the Forsmark area is strongly affected by recovery from the isostatic depression caused by ice-sheet loading during the preceding interglacial period. Immediately following a glaciation, after retreat of the ice-sheet towards the north-west, the site is projected to be submerged. However, as isostatic recovery outpaces global sea-level rise, the shoreline is expected to retreat eastward and new areas of land are expected to emerge. Assuming global warming to be of short duration and taking the next glacial cycle to be similar to the last (the Weichselian), the projected future climate-related characteristics of the Forsmark site are as shown in Figure A.6.

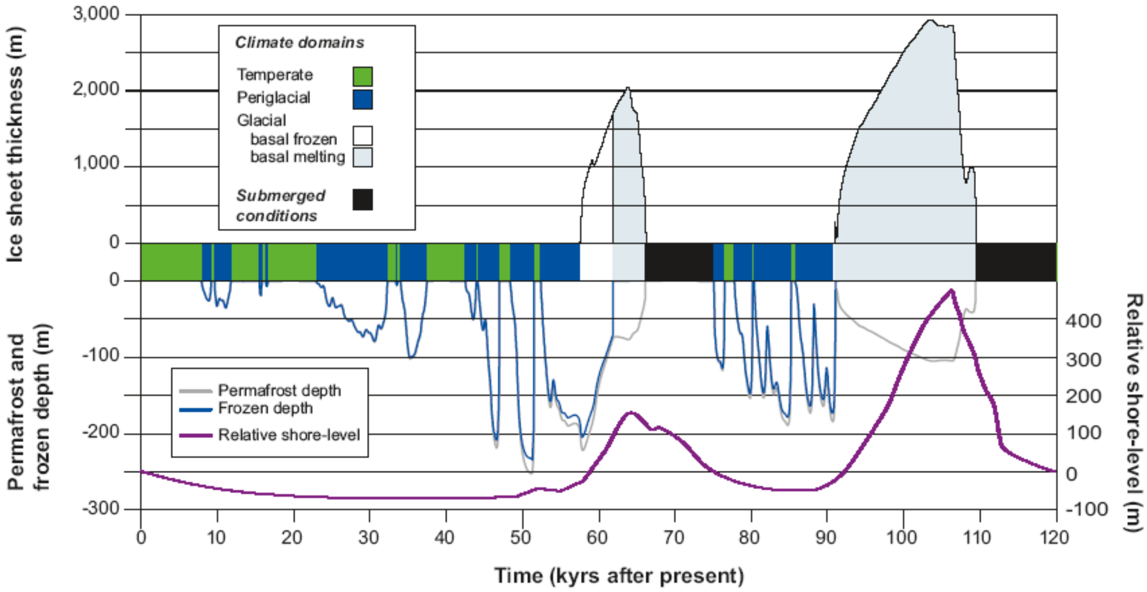


Figure A.6: Future Climate-related Characteristics of the Forsmark Site, assuming a Repetition of the Weichselian Glacial-interglacial Cycle (Figure 10-107 of SKB, 2011)

The regional context of the site in the early part of an interglacial period is well illustrated by the reconstructed palaeoenvironmental characteristics since the Last Glaciation. This is illustrated schematically in Figure A.7; corresponding hydrogeochemical changes are shown schematically in Figure A.8.

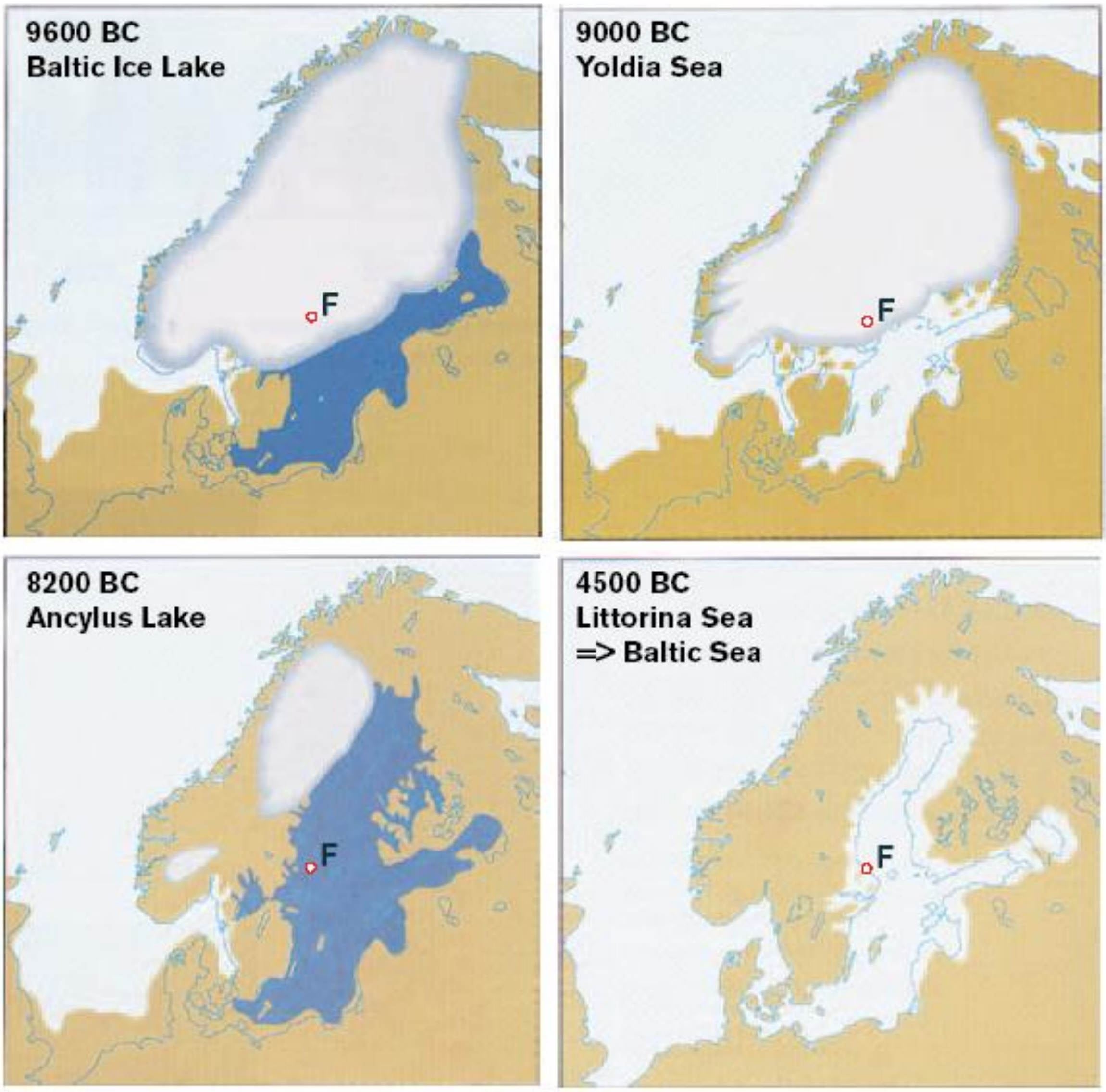


Figure A.7: Map of Fennoscandia with some Important Stages during the Holocene Period. Four main stages characterise the development of the aquatic systems in the Baltic basin since the latest deglaciation: the Baltic Ice Lake (13,000–9500 BC), the Yoldia Sea (9500–8800 BC), the Ancylus Lake (8800–7500 BC) and the Littorina Sea 7500 BC–present). Fresh water is symbolised with dark blue and marine/brackish water with pale blue. The Forsmark area (notated 'F') was probably at or close to the rim of the retreating ice sheet during the Yoldia Sea stage. [Figure 4-20 of SKB, 2011].

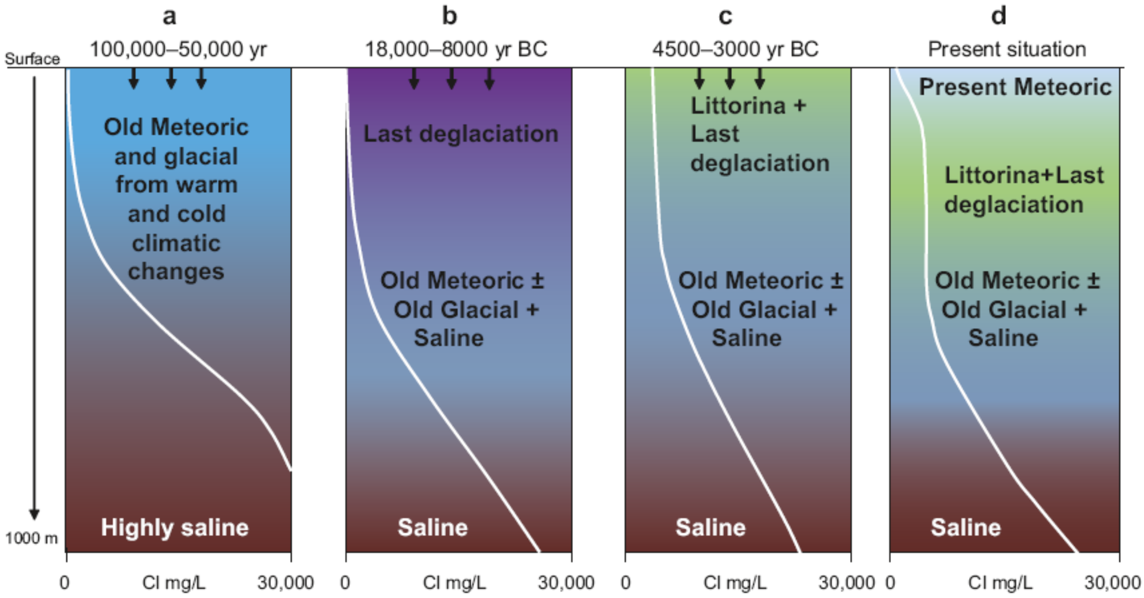


Figure A.8: Sketch showing Tentative Salinities and Groundwater-type Distributions versus Depth for the Transmissive Zones at Forsmark. From left to right: a) situation prior to the last deglaciation, b) last deglaciation and intrusion of meltwater, c) the Littorina Sea water penetration caused by density intrusion, and d) the present situation. Tentative salinity profiles are indicated by the white lines. Figure 9-4 of SKB [2008].

The future evolution of the Forsmark site during the remainder of the current interglacial is expected to be governed by continuing isostatic uplift and further shoreline displacement. This is discussed further in Section 2.3.3.

A.3.3 Environmental Change and the Geosphere-Biosphere Interface

Changes in the Environment at Forsmark

In its safety assessment studies, SKB (2011) distinguishes three periods. These are:

- The initial period of temperate conditions after closure;
- The remaining part of the reference glacial cycle;
- Subsequent glacial cycles.

In relation to these three different climatic regimes, SKB is undertaking research at three sites, Forsmark, Krycklan (an established research area in northern Sweden that is a good analogue for Forsmark under a slightly cooler climate) and Greenland, which has similar bedrock to the Forsmark region and is considered a good analogue of future periglacial conditions.

A reference case and a global warming variant of the reference case are investigated. However, the global-warming case does not introduce any additional considerations into the definition of the GBI and it is not considered further.

During the initial period of temperate conditions, the present regressive shoreline displacement will continuously bring new areas of the sea floor above the wave base. This will expose sediments to wave erosion and resuspended fine-grained particles will be transported out of the area into the Bothnian

Sea, or re-settle on deeper bottoms. Accordingly, the relocation of sediments may have important implications for transport and accumulation of radionuclides potentially originating from a future repository [SKB, 2011; Section 10.3.3].

When new areas of the present seafloor are raised above the sea level, weathering of the calcium-rich Quaternary deposits is initiated. Most of the easily weathered calcite in the upper regolith will be dissolved and washed out within a period of some thousands of years. This means that the strong influence of the calcium-rich deposits on the terrestrial and limnic ecosystems will be reduced over time. For instance, the oligotrophic hard water lakes that are characteristic of the coastal area in Forsmark will likely be transformed to more dystrophic (low pH, brown-water) conditions within some thousands years after isolation from the sea [SKB, 2011; Section 10.3.3].

The shoreline displacement will also cause a continuing and predictable change in the abiotic environment, e.g. in water depth and nutrient availability. It is therefore appropriate to describe the origin and succession of major ecosystem types in relation to shoreline displacement. One example of this is the isolation of a sea bay into a lake, followed by the ontogeny of the lake and its development into a wetland. As the lake ages, sediment and organic matter accumulate due to sedimentation and vegetation growth, and eventually all lakes are transformed to wetlands. The rate of sedimentation decreases with decreasing lake volume, whereas the colonisation of littoral plants requires shallow water (< 2 metres).Thus, the rate of lake infilling is mainly dependent on lake depth, area and volume. Mires may also develop on newly emerged land without a preceding lake stage [SKB, 2011; Section 10.3.3].

Over the next 1,000 years, the shoreline is projected to retreat about 1 km to the east of the site (Figure A.9). However, overall, the biosphere at the site during the next 1,000 years is assumed to be quite similar to the present situation. The most important changes are the natural infilling of lakes and a slight withdrawal of the sea with its effects on the near-shore areas and the shallow coastal basins.

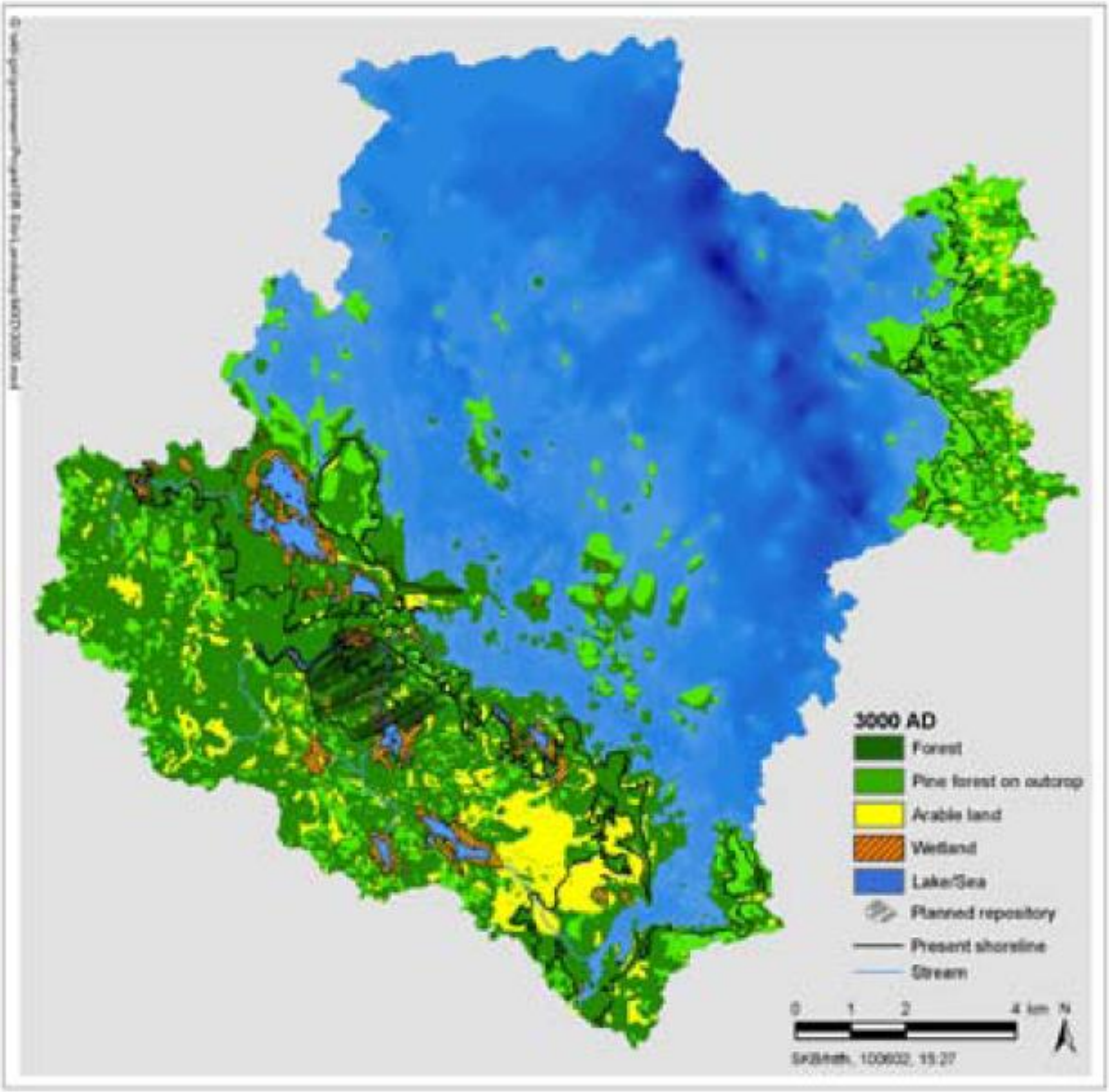


Figure A.9: Modelled Distribution of Vegetation and Land Use in Forsmark at 3000 AD. All areas that potentially can be cultivated are represented on the map as arable land (see Chapter 4 in Lindborg, 2010). The present shoreline is marked as a black line and darker shades of blue represent deeper sea. Figure 10-11 of SKB [2011].

According to the SR-Site reference glacial cycle, temperate conditions will persist in Forsmark until c. 10,000 AD. During this period, the regressive shoreline displacement is assumed to continue, but at a gradually declining rate [Lindborg, 2010]. Initially, the coastline will be subject to a horizontal transfer of approximately 1 km per 1,000 years. This will strongly influence the landscape; especially during the first part of the period, and eventually it will result in a situation where the planned repository will have an inland rather than a coastal setting (see Figure A.10).

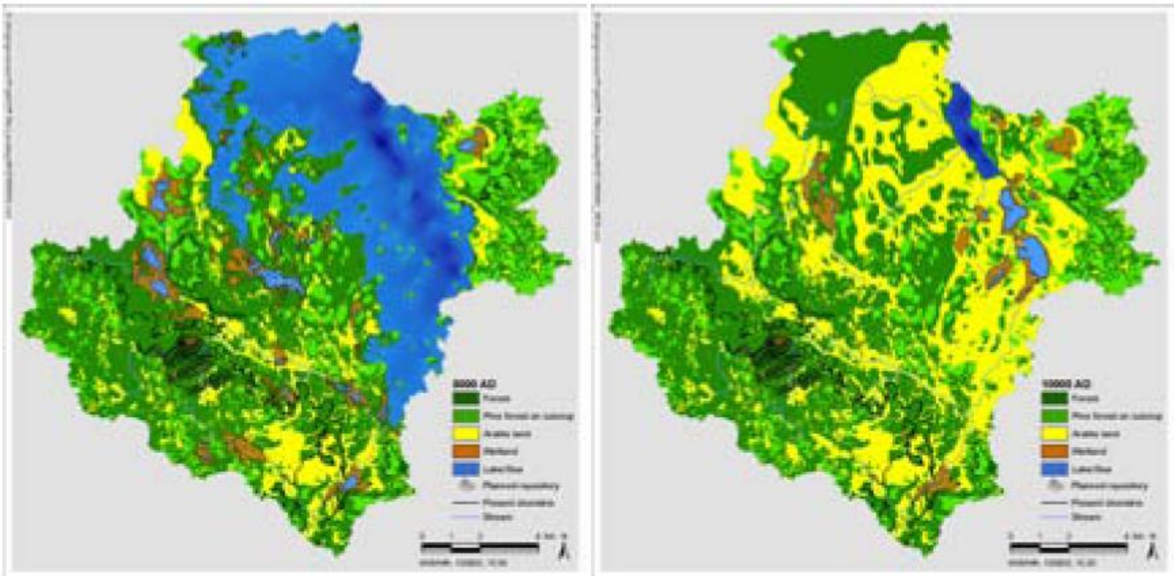


Figure A.10: Modelled Distribution of Vegetation and Land Use in Forsmark at 5000 AD and at 10,000 AD. All areas that potentially can be cultivated are represented on the map as arable land. The present shoreline is marked as a black line and darker shades of blue represent deeper sea. Figure 10-12 of SKB [2011].

The strait at Öregrund, south of the modelled area, is expected to be cut off about 3000 AD, and Öregrundsgrepen will turn into a bay. This will affect the water circulation, and, due to the continued narrowing of the bay, the water turnover will be further restricted. However, at the beginning of the period it is not expected to be longer than a couple of weeks, except for minor sub-basins which are near isolation. During the period from 3000 to 5000 AD, a semi-enclosed archipelago is expected to develop northeast of the repository. Around 5000 AD, many straits in this archipelago will close and a number of lakes will be isolated from the sea.

At 5000 AD, the coastline has withdrawn c. 5 km from the repository. A small stream drains the area above the repository, and some small and shallow lakes are expected to be situated along the stream.

This small stream will join a large stream in the south-east at about 5000 AD. This large stream consists of the merged Forsmarksån and Olandsån, draining a large part of Northern Uppland (drainage area $1.3\ 10^3\ km^2$). During the period from 3000 AD to 10,000 AD, the Öregrundsgrepen bay gradually shrinks to finally form a short and narrow bay along the island of Gräsö (Figure A.10).

In the modelled area, a large number of lakes will be isolated from the sea during the period from 3000 AD to 10,000 AD. Most of the new lakes are small and shallow, and are expected to be infilled and transformed into mires within a period of 2,000 to 6,000 years.

Around 10,000 AD, almost all lakes in the area have been infilled and only some initially relatively large and deep lakes near Gräsö Island are expected to remain (Figure A.10).

The salinity of the sea will continuously decrease due to the isostatic rebound of the shallow sills at Åland between the Bothnian Sea and the Baltic Proper. Around 6000 AD, the salinity is expected to have decreased to 3–4‰, which means that an ecosystem with lower abundance of marine species and higher of freshwater species, will develop.

Accumulation of sediments may occur both on bottoms at large water depths and on shallow bottoms that are sheltered from wave exposure inside a belt of skerries. Erosion occurs mainly on shallow bottoms exposed to waves. Transport bottoms can be found in all places between these two extremes, i.e. at intermediate depth with moderate wave exposure. This means that the seafloor in the model area will show a characteristic evolution over time, beginning with a period of accumulation due to large water depth early after deglaciation. Then comes a period with transport, after which erosion dominates when the water depth decrease even more. Finally, transport and accumulation may occur in sheltered locations during a short period before the sea bottom becomes land. This means that there are very limited parts of the model area that will show continuous accumulation of sediments throughout the whole marine period. The small areas that potentially may show continuous accumulation since the latest deglaciation are situated in the deepest parts of Öregrundsgrepen.

Much of the newly formed land will be unsuitable for farming due to boulder- and stone-rich deposits, but there are large areas in central Öregrundsgrepen with fine-grained sediments that can be cultivated. Also patches of organic soils on previous lakes/mires may be cultivated, but presumably these soils can be sustainably utilised only for limited periods, since compression and oxidation of the organic material will lower the ground surface and cause problems with drainage.

The food productivity in agricultural areas is several hundred times higher than that in aquatic or non-cultivated terrestrial areas. Since the proportion of land that it is possible to cultivate will increase as new land areas are formed, this means that the potential food productivity in the total modelled area is expected to increase during the period. However, the number of people that potentially can be sustained by food produced within the Forsmark area is strongly dependent on the degree to which land is used for farming.

The availability of freshwater for human supply is expected to gradually increase. As mentioned above, new lakes and streams will form, but most of the lakes will be short-lived due to their shallowness.

New groundwater, potentially useful as drinking water, will be available when the shoreline moves eastwards. Among already existing geological formations, the Börstilåsen esker, situated c. 4 km southeast of the planned repository, may provide groundwater of drinking-water quality, but there are no indications in the hydrogeological modelling results that this aquifer will have contact with discharging groundwater from the repository.

Over the remaining part of the reference glacial-interglacial cycle, three characteristic climate domains can be expected to occur (temperate, periglacial and glacial). In addition, periods when the ground above the repository is submerged, either by the Baltic Sea or by a fresh water lake, can be expected. During submerged periods, the climate conditions can either be temperate or periglacial, the latter yielding permafrost development in areas not covered by the sea/lake. The evolution of climate-related conditions is described as time series of climate domains and submerged periods.

The temperate climate domain corresponds to 26% of the reference glacial cycle. After the initial temperate period, which according to the reference glacial cycle ends around 9400 AD, a relatively short period of periglacial conditions follows, and thereafter temperate conditions again dominate until c. 23,000 AD. Another temperate period lasting for about 5,000 years occurs around 40,000 AD.

During future periods of temperate conditions before the next glaciation, Forsmark is assumed to show biosphere characteristics similar to those of the later parts of the initial temperate period, i.e. the landscape will consist of terrestrial ecosystems, mainly forests and mires, with few or no lakes and no sea. Parts of the area, especially those with fine-grained sediments in central Öregrundsgrepen, can potentially be used for long-term agriculture.

Patches with mainly organic soils may also be cultivated for limited periods. Higher altitude areas with outcrops of bedrock will be forested with pine. Also, the pattern of discharge of deep groundwater and the conditions determining transport and accumulation of radionuclides in the landscape are expected to be similar to those prevailing during the late part of the initial temperate period.

Periods of periglacial conditions, which are characterised by tundra vegetation and permafrost features, correspond to 34% of the reference glacial cycle. Although the periglacial domain constitutes the largest share of the reference glacial cycle, it often occurs during relatively short periods interrupted by other climate domains. The longest uninterrupted period of periglacial conditions starts around 23,000 AD and continues for c. 10,000 years.

The vegetation period in the periglacial domain is short. Nevertheless, primary production may be high in some environments, e.g. in shallow lakes. The terrestrial vegetation consists of sedges, herbs and shrubs. At more exposed and dryer localities, lichens dominate, whereas wet ground is dominated by mosses. The precipitation will likely be lower than during temperate conditions, due to the limited evapotranspiration transporting water to the atmosphere. The low evapotranspiration means that wet ground is prevalent, because surplus water is unable to infiltrate into the ground. This may result in larger areas of wetlands compared with a temperate climate, but on the other hand the peat formation rate is lower, partly because the terrestrial plant productivity is low.

Even on gentle slopes, the soil creeps downhill with the peat cover on top. Other processes typical of periglacial conditions are upward migration of stones induced by freeze-thaw processes, so called cryoturbation, causing tundra-polygons (patterned ground whose mesh is tetragonal, pentagonal or hexagonal) and thermokarsts (topographic features produced by thawing permafrost and associated settling of the ground).Thus, there are many processes disturbing the soil and also exposing it to erosion.

Taliks are unfrozen areas, often occurring under lakes or rivers in the permafrost region. The talik features are the only spots in the periglacial landscape where radionuclides released from the repository can be transported up to the biosphere. Given that lakes and streams often are locations for human settlement and land use, taliks can potentially be locations where humans are exposed to high radionuclide concentrations during periglacial conditions. However, the generally low productivity in the permafrost region requires utilisation of a larger area to supply the resources needed by even a small community. Therefore, even if radionuclides are discharged into a talik in such an area, this does not necessarily imply that the average concentrations in the food consumed by humans living in the area will be particularly high.

Forsmark is covered by an ice sheet during 24% of the reference glacial cycle, mainly during the later part of this cycle. On the ice surface, microbes, algae and some insects can exist. At the ice-margin, a productive aquatic community may exist, which can sustain fish populations that may be exploited by humans and by animals living on the ice (e.g. birds, polar foxes, polar bears) and in the sea (e.g. seals and whales).

Any larger vertebrates or humans living on the ice are likely to migrate over large areas due to low food production and severe weather conditions. In most cases, a human population will probably comprise occasional visitors, due to the harsh environment. The only situation under glacial conditions when humans or other biota may be exposed to high concentrations of radionuclides from the repository is when the retreating ice-front is situated near the Forsmark area and the area is submerged. Under these conditions, it is possible that a human population could be present for longer periods and live on fish taken from close to the ice margin.

During periods of glacial climate domain, no long-term accumulation of radionuclides is assumed to occur in the regolith due to the short turnover time of this potential reservoir. It is only during short periods of the glacial climate domain that radionuclides discharged from underground sources may accumulate as under periglacial conditions. However, since the Forsmark site will be depressed below the sea level during most of the glacial periods, fast water turnover in the open sea along the ice margin will probably dilute any released radionuclides and prevent the accumulation of high concentrations in sediments and organisms.

In the reference glacial cycle, two periods of submerged conditions at Forsmark are present, representing 16% of the total reference glacial cycle. These periods always follow directly after the ice sheet has withdrawn as a result of the bedrock being depressed by the ice load. After the last glaciation which ended at 8800 BC in Forsmark, the first terrestrial areas appeared around 1000 BC and the last marine embayment in the modelled area is turned into a lake around 11,000 AD. This means that the submerged conditions in the modelled area may be divided into two phases; one first phase of c. 8,000 years when the whole area is submerged, and another that continues during 12,000 years when the sea gradually withdraws and the land area expands accordingly.

Submerged conditions are not defined as a climate domain in SR-Site. Instead, it is a state when the processes and properties related to the marine conditions are dominant.

The marine ecosystem is not expected to change dramatically from today as a result of changes in climate, except for the long-term variations in salinity. Therefore, the submerged future landscape is in SR-Site treated as corresponding to the historical and present aquatic ecosystems at Forsmark, and the prerequisites for transport and accumulation of radionuclides are assumed to be similar to those in the present marine ecosystem.

For the reference climatic evolution, the first glacial cycle is simply assumed to be repeated until the end of the one million year assessment period. With a cycle period of around 120,000 years, this means about seven repetitions of the initial Weichselian glacial cycle, i.e. a total of eight such cycles.

Radionuclide Discharge Locations

The changing position of the coastline means that radionuclide discharge locations alter as the landscape alters. This is discussed in Section 13.2.6 of SKB [2011], where it is reported that the hydrogeological models [Joyce *et al*., 2010; Bosson *et al*., 2010] predict that discharge areas will primarily be located in low points of the landscape such as lakes, wetlands and shallow parts of the sea floor. According to Joyce *et al*. [2010], the discharge pattern is determined mainly by the local topography and the deterministic deformation zones, and the pattern does not vary significantly among model realisations. Detailed surface hydrological modelling confirmed the overall pattern of the location of discharge areas in Forsmark [Bosson *et al*., 2010].

In the near-surface, the higher intensity of fracturing needs to be taken into account in determining the routing of radionuclides to discharge locations. This is illustrated schematically in Figure A.11.

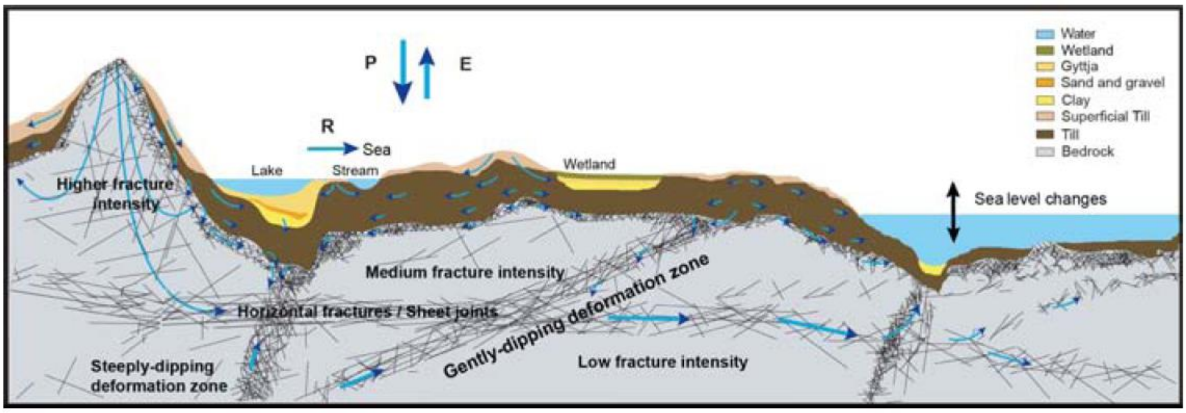


Figure A.11: Cross-section Cartoon visualising the Notion of a Shallow Bedrock Aquifer and its Envisaged Impact on the Groundwater Flow System in the Uppermost Part of the Bedrock within the Target Area. The shallow bedrock aquifer is probably hydraulically heterogeneous, but at many places it is found be very anisotropic causing a short circuit of the recharge from above. The shallow bedrock aquifer is conceived to constitute an important discharge horizon for the groundwater flow in outcropping deformation zones.

(P = precipitation, E = evapotranspiration, R = runoff). Figure 4-18 of SKB [2011].

Landscape Modelling and the Identification of Biosphere Objects

The main objectives of the biosphere assessments in the SR-Site project were to produce values of landscape dose conversion factors that allow translation of a potential release from a geological repository to the exposure of humans inhabiting the Forsmark site in the future, and to assess the exposure of other organisms in the area. The landscape dose conversion factors are used in the safety assessment for obtaining estimates of doses to humans, which, in turn, are used in demonstrating compliance with the regulatory criteria [Section 13.2.1 of SKB, 2011].

To accomplish this, areas with potential discharge of deep groundwater from the repository, called biosphere objects, were identified at the site, and the long-term development of these areas was modelled. A biosphere object is defined as an area of the landscape that potentially may receive radionuclides released from a future repository, either through discharge of deep groundwater or by contaminated surface water, at any time during a glacial cycle. In SR-Site, the biosphere at Forsmark was represented by a set of interconnected biosphere objects [see Lindborg, 2010 for details].[a]

The transport and accumulation of radionuclides in the biosphere objects throughout a full glacial cycle was then described with the radionuclide model for the biosphere. The biological uptakes by various organisms, some of which are potential food sources for humans, were calculated from activity concentrations in the environment (air, soil, water and food). Finally, assumptions on land use and

[a] The landscape model is linked to the geosphere model, enabling flow paths from the geosphere for different times and climate scenarios to be evaluated and to determine how climate change and landscape development affect discharge locations in the biosphere. The geosphere is modelled continuously from repository depth to the ground surface. Deep permafrost, if present, has a large influence on groundwater flow resulting in fewer, more localised discharges.

human habits were used in combination with activity concentrations in the environment, to calculate landscape dose conversion factors for future human inhabitants. The activity concentrations were also used to assess the potential future exposures of other organisms at the site. The biosphere objects used at Forsmark are illustrated in Figure A.12.

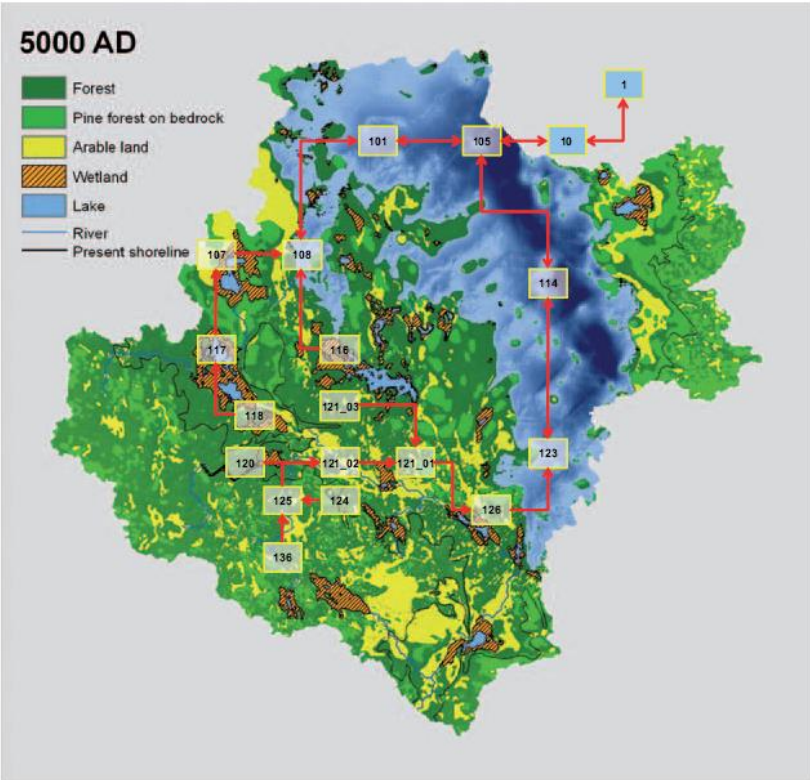


Figure A.12: The Location and Hydrological Connections of Biosphere Objects in the SR-Site Assessment, displayed on a Map of the Forsmark Landscape at 5000 AD. Figure 13-5 of SKB [2011].

The radionuclide transport model for each biosphere object is a compartment model, where system components that are considered internally homogeneous in their properties are represented by distinct compartments.

A graphical representation of the conceptual model is shown in Figure A.13, where each box corresponds to a model compartment. Definitions of the model compartments are presented in the figure.

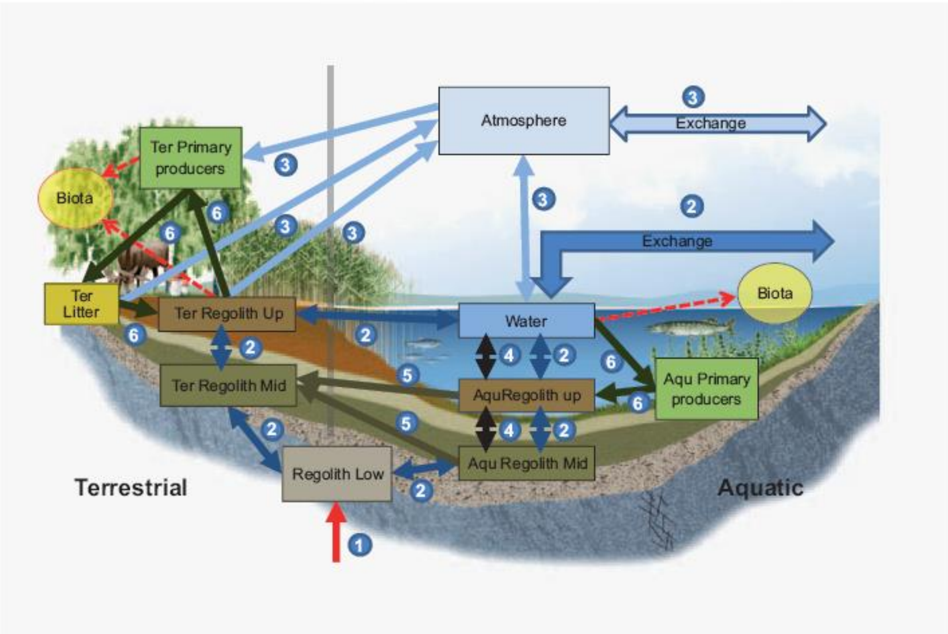
The arrows in Figure A.13 represent radionuclide fluxes between compartments and fluxes into and out of the system. Radionuclide fluxes are linked to the movement of matter in the biosphere, i.e. water flow, particle transport and gas emanation and transport. Radionuclide transfers that are mediated by biota, like uptake and release by primary producers, have also been represented. The arrow reaching the lower regolith compartment represents radionuclide release from the geosphere into the biosphere object. The release is directed to the deeper parts of the regolith, which at the site normally consists of glacial till deposited on the bedrock.

Radionuclides released to the lower regolith compartment are distributed to the upper layers of the ecosystems by advection and diffusion. The representation of the waterborne transport of radionuclides between compartments is based on detailed hydrological modelling with MIKE-SHE [Bosson *et al*., 2010]. The effect of radionuclide sorption on the advective and diffusive transport is taken into account by assuming equilibrium between the pore water and the solid phase of the different compartments. The model also considers the transport of radionuclides absorbed to suspended particles, driven by surface water fluxes, sedimentation and resuspension processes.

The radionuclide transport mediated by biota is, for both terrestrial and aquatic ecosystems, described in the model through fluxes driven by net primary production.[a] It is assumed that equilibrium is established between the activity concentrations of radionuclides in the newly produced biomass and in the corresponding environmental media (upper regolith for terrestrial and water for aquatic ecosystems). Losses from the upper regolith and surface waters via degassing processes are pessimistically neglected for all radionuclides, except for C-14 for which this process was explicitly considered, since uptake from air through photosynthesis is the dominant pathway for incorporation into terrestrial primary producers.

Biosphere objects may, beside a release to the lower regolith, also receive radionuclides with surface water from contaminated biosphere objects located upstream or in adjacent marine bays (exchange arrows in Figure A.13). In initial simulations, the radionuclide model was implemented for each identified biosphere object in a network according to the flux of surface water in the landscape (see Figure A.12). These simulations showed that the maximum unit release dose was always found in a biosphere object that received a direct release from the geosphere, and that the dose resulting from the indirect release to the same object via an adjacent object was typically an order of magnitude lower. As the aim of the biosphere assessment was to identify the most exposed group across all biosphere objects, indirect contamination was not considered in the assessment, in order to simplify the analysis with separate simulations for each object.

[a] It is important to recognise that the sizes of 'pools' of elements and other materials are affected by the evolution of the landscape, as are the processes determining transport between those pools and the rates of transport.



Model name	Description
Regolith Low	The lower part of the regolith overlying the bedrock, primarily composed of till. It is common to the terrestrial and aquatic parts and its origin is from the glaciation.
Aqu Regolith Mid	The middle part of the regolith in the aquatic part of biosphere objects, usually consisting of glacial and postglacial clays, gyttja and finer sediments which originate mainly from the period after the retreat of the glacial ice sheet, or from later resuspended matter mixed with organic sediments.
Aqu Regolith Up	The part of the aquatic regolith with highest biological activity, comprising c. 5–10 cm of the upper aquatic sediments where resuspension and bioturbation can maintain an oxidising environment.
Ter Regolith Mid	The middle part of the terrestrial regolith, containing glacial and postglacial fine material, i.e. former sediments from the seabed / lake bottoms.
Ter Regolith Up	The upper part of the terrestrial regolith which has the highest biological activity, like the peat in a mire, or the plowing layer in agricultural land.
Litter	Dead plant material overlying the regolith.
Water	The surface water (stream, lake, or sea water).
Aqu Primary Producers	The biotic community in aquatic habitats, comprising both primary producers and consumers.
Ter Primary Producers	Terrestrial primary producers.
Atmosphere	The lower part of the atmosphere where released radionuclides are fully mixed.

Figure A.13: Conceptual Illustration of the Radionuclide Model for a Biosphere Object. Boxes represent compartments, thick arrows fluxes, and dotted arrows concentration computations for non-human biota (these are not included in the mass balance). The model represents one object which contains an aquatic (right) and a terrestrial part (left) with a common lower regolith and atmosphere. The source flux (1 Bq/y) is represented by a red arrow (1). The radionuclide transport is mediated by different major processes, indicated with dark blue arrows for water (2), light blue for gas (3), black for sedimentation/resuspension (4), dark brown for terrestrialisation (5), and green for biological uptake/decomposition (6). Import from and export to surrounding objects in the landscape is represented by arrows marked "exchange". Brief descriptions of the compartments are given in the table below the figure. Based on Figure 13-6 and Table 13-1 of SKB [2011].

The biosphere objects, as illustrated in Figure A.13 were subject to time-dependent changes in their characteristics to reflect the overall time-evolution of the landscape described above. As illustrated in Figure A.13, the model of a biosphere object has two parts, one aquatic (right side of Figure A.13) and one terrestrial (left side of Figure A.13). The temporal development of an object is handled by varying the sizes and properties of these two parts in accordance with the simulated natural development of the specific biosphere object [see Lindborg, 2010 for details]. Thus, most biosphere objects are expected to experience four main stages, as summarised below.

Sea stage: The biosphere object is a sea bay which, as the landscape emerges from the sea, is continuously reduced in size. During this period, the object is totally dominated by the aquatic part, and the fluxes from the deep regolith layers are consequently directed only to the aquatic sediments (mid and upper regolith);

Transitional stage: The sea bay is isolated and transforms into a lake or a stream (aquatic part), surrounded by wetland (terrestrial part). The isolation of a lake in the Forsmark area takes typically around 500 years [Lindborg, 2010] and during this period saltwater flooding will occur periodically. Fluxes from the deep regolith layers are apportioned to the aquatic and the terrestrial parts according to their relative sizes. During the transitional stage, parameter values for the aquatic part are changed linearly from sea to lake values.

Lake stage: The surrounding wetland expands into the lake, and the aquatic sediments are gradually covered by a layer of peat. This process is represented by a flux of radionuclides bound to the regolith from the aquatic to the terrestrial regolith layers. The lake stage ends when the lake has been fully transformed into a wetland, intersected by a small stream.

Terrestrial stage: The biosphere object has reached a mature state and no further natural succession occurs. The end stage is a wetland with a small stream If the wetland has a suitable size and regolith composition for agriculture, it may potentially be cultivated at any time in the future and this agricultural use is represented in the model.

A.4 THE SAFETY CASE DEVELOPED BY POSIVA OY FOR A REPOSITORY AT OLKILUOTO

A.4.1 Assessment Context

In Finland, according to the Nuclear Energy Act of 1987 and including amendments made up to Act 342/2008 and Act 410/2012:

- Nuclear waste, including spent nuclear fuel, generated in Finland must be processed, stored and disposed of in Finland, and
- All practical and financial measures to ensure the safe and secure management and disposal are the responsibility of the nuclear power companies that produce the waste.

In view of these considerations, in 1995, the two Finnish nuclear power companies, Teollisuuden Voima Oy (TVO) and Imatran Voima Oy (later Fortum Power and Heat Oy (Fortum)) established Posiva Oy (Posiva) to implement the final disposal programme for spent nuclear fuel and to carry out related research, technical design and development (RTD or TKS in Finnish). Other nuclear wastes are managed and disposed of by the power companies themselves.

On assignment by its owners, Fortum and TVO, Posiva will take care of the disposal of spent fuel from the nuclear power plants at Loviisa and Olkiluoto. At Loviisa, two Russian-designed pressurised water reactors (VVER-440) are in operation; at Olkiluoto, two boiling water reactors (BWR) are operating and one pressurised water reactor (EPR) is under construction. Plans exist for a fourth nuclear power unit at Olkiluoto. At both sites, there are facilities for interim storage of the spent fuel before disposal.

In 2001, the Parliament of Finland endorsed a Decision-in-Principle (DiP) whereby the spent nuclear fuel produced by the operating Loviisa and Olkiluoto reactors will be disposed in a geological repository at Olkiluoto. This first DiP allowed for the disposal of a maximum amount of spent nuclear fuel corresponding to 6500 tonnes of uranium (tU) initially loaded into the reactors. Subsequently, additional DiPs were issued in 2002 and 2010 allowing extension of the repository (up to 9000 tU) to accommodate spent fuel from the operations of the OL3 reactor and the planned OL4 reactor.

The proposed method of disposal at Olkiluoto is the KBS-3V method, as proposed by SKB (see Section A.3.1) and the aim is for the repository to begin operations in 2020. A schematic of the proposed repository at Olkiluoto is shown in Figure A.14.

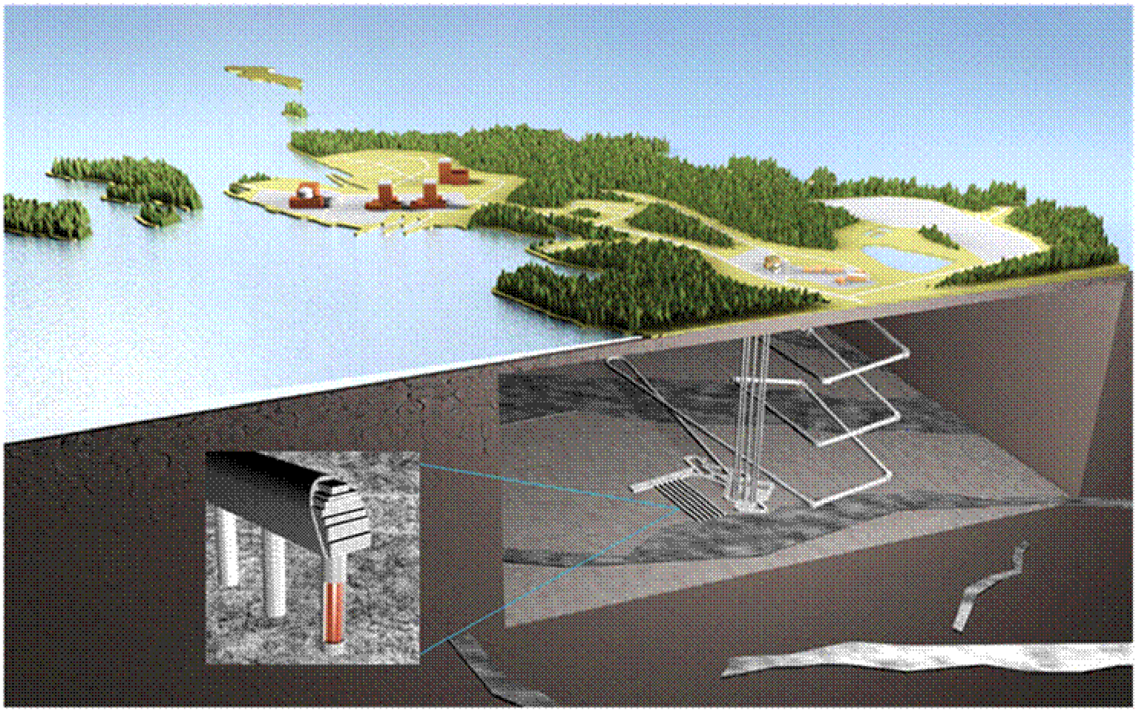


Figure A.14: Schematic Illustration of the Proposed KBS-3V Repository at Olkiluoto [from Figure 2-1 of Posiva, 2012].

The assumptions and models used in assessments are strongly driven by regulatory requirements, particularly relating to the level of conservatism that should be applied. Also, there is a requirement specific to Finland to evaluate radiation doses both to the most exposed people and to the rest of the population. Dose rates to non-human biota must also be evaluated. As it is not plausible to define cautious release assumptions in a single assessment scenario for each of these endpoints, multiple release scenarios have to be evaluated.

A.4.2 Geological and Environmental Context

The Olkiluoto site, located on the coast of south-western Finland (Figure A.15), has been investigated as a potential site for the underground disposal of spent nuclear fuel for over 25 years. This has included the construction of an underground rock characterisation facility (ONKALO). Olkiluoto Island has an area of about 10 km^2; the surface facilities including the encapsulation plant will occupy about 0.1 km^2;

according to the current design and capacity, the deposition tunnels and other tunnels will occupy about 2 km^2.

Figure A.15: Olkiluoto Island is situated on the Coast of the Baltic Sea in South-western Finland. Photograph by Helifoto Oy. Figure 2-2 of Posiva [2012].

The crystalline bedrock of Finland, of which Olkiluoto Island is composed, is part of the Precambrian Fennoscandian Shield, which, in south-western Finland comprises the Svecofennian domain that developed between 1930 Ma and 1800 Ma ago. The rocks of Olkiluoto consist of two major classes: high-grade metamorphic rocks including gneisses with varying degree of migmatisation, and igneous rocks including pegmatitic granites and diabase dykes (Figure A.16). The bedrock has been affected by five stages of ductile deformation resulting in lithological layering, foliation, strong migmatisation and folding. Extensive hydrothermal alteration has also affected the properties of fractures and certain rock volumes, the main alteration minerals being illite, kaolinite, sulphides and calcite. As a result, the rock properties at Olkiluoto are heterogeneous, which is reflected also in the variation of the thermal and rock mechanics properties.

The fault zones at Olkiluoto are mainly SE-dipping thrust faults formed during the latest stages of the Svecofennian orogeny, approximately 1800 Ma ago, and were reactivated in several deformation phases (see Figures A.16 and A.17). In addition, NE-SW striking strike-slip faults are also common. The occurrence of fracturing varies between different rock domains, but the following three fracture sets are typical for the site: (i) east-west striking fractures with generally sub-vertical dips to both the north and south, (ii) north-south striking fractures with generally sub-vertical dips to both the east and the west and (iii) moderately-dipping to gently-dipping fractures with strikes that are generally sub-parallel to the aggregate foliation directions in a particular fracture domain.

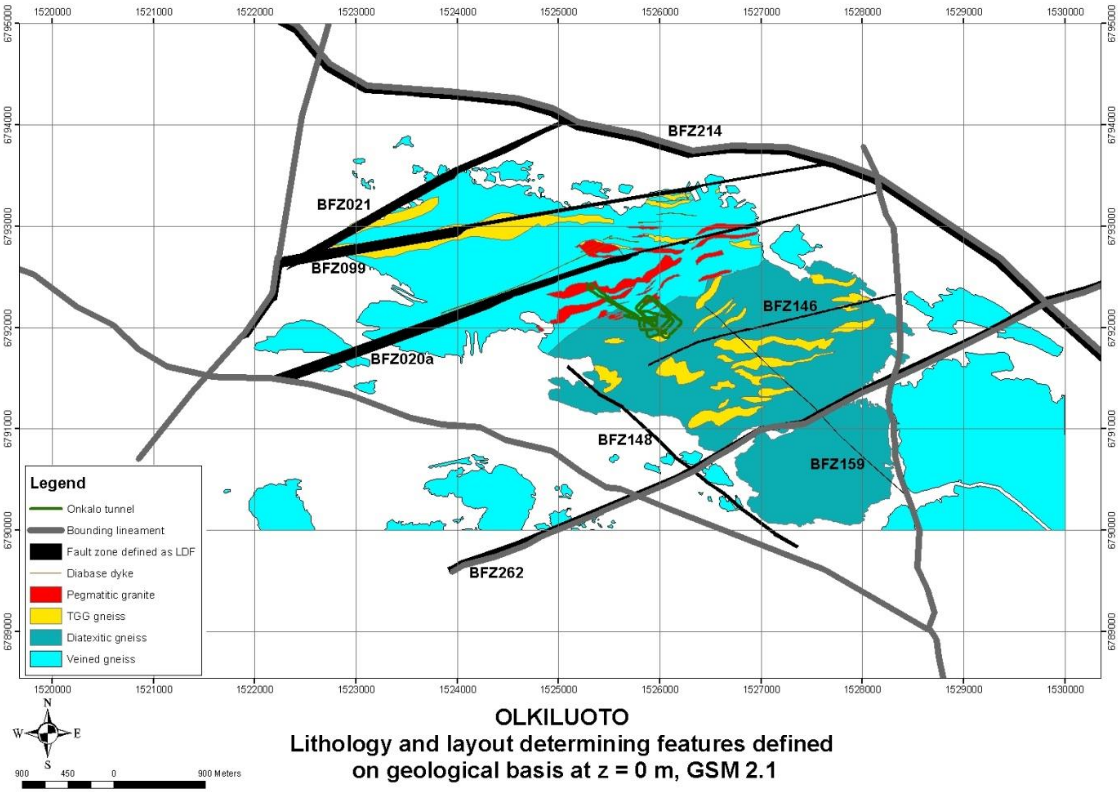


Figure A.16: A Geological Map of Olkiluoto Island showing the Lithology and the Brittle Fault Zones defined as Layout Determining Features, i.e. Ones that Restrict the Repository Layout. Figure 3-1 of Posiva [2012].

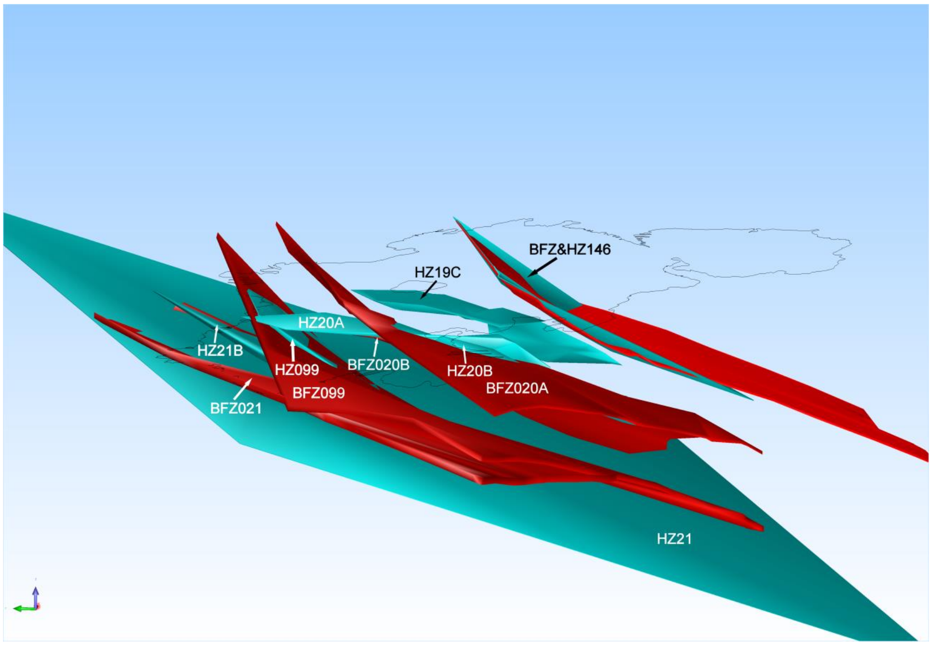


Figure A.17: Main Hydrogeological Zones at Olkiluoto (HZ in blue) and their correlation with the Fault Zones (BFZ, in red). The outline of the island is also shown in the figure. Figure 3-2 of Posiva (2012).

In the crystalline bedrock at Olkiluoto, groundwater flow takes place in hydraulically active deformation zones (hydrogeological zones) and fractures. The larger-scale hydrogeological zones, which are related to brittle deformation zones, carry most of the volumetric water flow rate in the deep bedrock. There is a general decrease of transmissivity of both fractures and the hydrogeological zones with depth. Under natural conditions, groundwater flow at Olkiluoto occurs mainly as a response to freshwater infiltration dependent on the topography, although salinity (density) variation driven flow also takes place to a lesser extent. The pore water within the rock matrix is stagnant, but exchanges solutes by diffusion with the flowing groundwater in the fractures.

The distribution of the groundwater types is the result of progressive mixing of groundwaters and the slow interaction between the groundwater, porewater and the minerals of the rocks (see Figure A.18). The groundwater composition is also affected by microbial activity. Water-rock interactions, such as carbon and sulphur cycling and silicate reactions, buffer the pH and redox conditions and stabilise the groundwater chemistry.

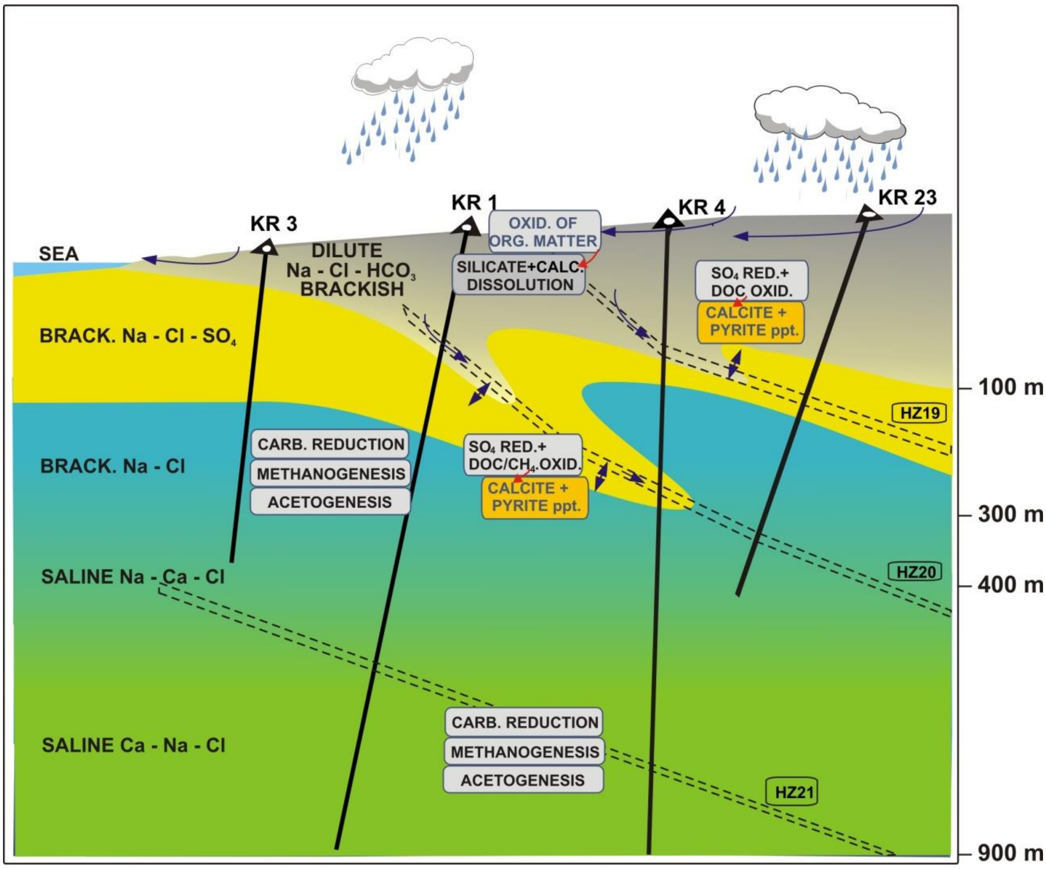


Figure A.18: Illustrative Hydrogeochemical Site Model of Baseline Groundwater Conditions with the Main Water-rock Interactions at Olkiluoto. Changes in colour indicate alterations in water type. The hydrogeologically most significant zones are represented. Blue arrows represent flow directions. Rounded rectangles contain the main sources and sinks affecting pH and redox conditions. Enhanced chemical reactions dominate the infiltration zone at shallow depths, and at the interface between Na-Cl-SO_4 and Na-Cl groundwater types. The illustration depicts hydrogeochemical conditions in the water-conductive fracture system, not in the diffusion-dominated rock matrix. Figure 3-3 of Posiva [2012].

Weathering processes during infiltration play a major role in determining the shallow groundwater composition at Olkiluoto. Pyrite and other iron sulphides are common in water-conducting fractures throughout the investigated depth zone indicating a strong lithological buffer against oxic waters over geological time scales. Groundwaters, in the range down to 300 m depth show indications of having been affected by infiltrating waters of glacial, marine and meteoric origin during the alternating periods of glaciations and interglacials during the Quaternary. On the other hand, these indications are absent in fracture groundwaters below 300 m, implying that these groundwaters are older.

The current fracture groundwater is characterised by a significant, depth-dependent variation of salinity (see Figure A.18). Fresh waters (<1 g/l) rich in dissolved carbonate are found at shallow depths, in the uppermost tens of metres. Brackish groundwater, with salinity up to 10 g/l dominates at depths between 30 m and about 400 m. Sulphate-rich waters are common in the depth layer 100-300 m, whereas brackish chloride water, poor in sulphate dominates at depths of 300-400 m. Saline groundwaters (salinity >10 g/l) dominate at still greater depths. The matrix porewaters seem to be in equilibrium with the fracture groundwaters in the upper part of the bedrock (0-150 m), suggesting a similar origin and strong interaction between groundwater in fractures and matrix at these depths. At deeper levels (150-500 m), the matrix porewater is less saline and increasingly enriched in $\delta^{18}O$; this has been interpreted to represent fresh water conditions during a warm climate, probably during the pre-glacial Tertiary period.

The topography in the Olkiluoto area, and in general in south-western Finland, is flat and soil erosion rates are very low. Glacial erosion features such as glacially smoothed bedrock outcrops and roches moutonnées are common. As a result of the last glaciation, the bedrock depressions are filled with a thicker layer of overburden, mainly sandy till and fine-grained till [Posiva, 2012].

The seawaters around Olkiluoto Island are shallow, except for a few areas where sea depths reach about 15 m. The seabed deposits in the surroundings of Olkiluoto are heterogeneous and the sediment thickness is variable. About 40-50% of the offshore is covered by till. The area of exposed bedrock or sedimentary rock on the seabed is about 15-20% of the offshore and various kinds of soft sediments cover about 20-30 % in the deeper open sea area and in sheltered near-shore basins. Littorina clays have been deposited in a marine environment, when environmental conditions in the sea were favourable for a moderately abundant fauna. Because of the amount of sedimented and intact organic material, these clays are gyttja clay in which there has often been gas formation, as a consequence of the breakdown of organic material. This is of particular interest because of the continued land uplift of the Olkiluoto area, which will expose areas of current seabed sediments in the next few thousand years – the time frame for which the radionuclide releases must be quantified in terms of annual effective doses to a human population and dose rates to other biota (see below). In addition, the effects of land uplift are accentuated by paludification e.g. reed bed growth in the coastal areas, especially in shallow bays [Posiva, 2012].

A.4.3 Environmental Evolution and the Geosphere-Biosphere Interface

Consideration of environmental evolution at Olkiluoto has been strongly conditioned by the regulatory context in which post-closure radiological safety assessments are undertaken. The relevant guidance is provided in STUK Regulatory Guide YVL D.5. This requires that, for expected evolution scenarios and in the period during which the radiation exposure can be assessed with sufficient reliability (at least over several millennia): the annual dose to the most exposed people shall remain below the value of 0.1 mSv and the average annual doses to other people shall remain insignificantly low. Beyond this initial period of several millennia, the radiological impacts of releases of radionuclides from the geosphere are to be assessed by comparing the release rates from the geosphere with radionuclide-specific limits on those release rates. Thus, biosphere modelling and consideration of the GBI is required only for the first several millennia after repository closure. In practice, the performance of the repository is considered by Posiva in three time windows: (1) during the excavation and operational period up to closure; (2) up until 10,000 years after closure; (3) beyond 10,000 years over repeated glacial cycles. Representation of the GBI is required only for the second of these time windows, i.e. to 10,000 years after closure.

Over the next 10,000 years, Posiva assumes that the climate will remain essentially as today, i.e. a temperate climate associated with a boreal ecosystem. Crustal uplift is assumed to continue, and as a consequence, hydraulic gradients will increase during the first few thousands of years after repository closure. After that, the shoreline has retreated far enough so that further changes in shoreline will not affect the hydraulic gradient nor alter the flow rates in the repository volume. Groundwater flow and groundwater chemistry will recover from the disturbances caused by the excavation to return to conditions similar to those of the present day. The groundwater flow is governed by the hydraulic gradients caused by the topography and salinity field. The main impact on the groundwater composition will be due to continued infiltration of meteoric waters. The main processes ongoing in the repository during this stage will be water uptake, saturation, swelling and homogenisation of the swelling clays in the buffer, backfill and closure and the gradual decline of the residual heat in the spent nuclear fuel [Posiva, 2012; Section 6.2].

Over this first 10,000 year period, Posiva considers that radionuclide releases can occur only from a canister with an initial penetrating defect. It is expected that most of the canisters can be technically manufactured as designed without any initial penetrating defect, and any penetrating defect greater than about 0.5 mm diameter is likely to be detected by weld inspection and testing. However, the currently available data are insufficient, even when expert judgement is used, to make a reasonable estimate of the probability of emplacing a defective canister in the repository. Nevertheless, with additional data on the welding process and continued development of the non-destructive testing process, it seems practicable in the future to show that the probability of more than one initially defective canister in the repository is less than one per cent. Thus, for the base scenario, one canister with an undetected penetrating defect of 1 mm diameter is assumed to be emplaced in the repository, both in the reference case and in other cases addressing this canister failure mode [Section 7.2.1 of Posiva, 2012].

The surface environment scenarios are formulated by Posiva independently from those relating to the repository system and are limited to the dose assessment time window, hence covering the first ten millennia after disposal. The base scenario for the surface environment is formulated bearing in mind that this time window is relatively short compared with the whole assessment time frame. The base scenario and its main assumptions are briefly summarised below. Variant scenarios are also considered, but these add little of relevance to characterisation of the GBI, so they are not discussed further.

Key statements in the regulations are that the environmental changes due to sea-level changes relative to the land (i.e. allowing for land uplift) should be considered, and that the climate type as well as the human habits can be assumed to remain unchanged (Guide YVL D.5, 307). Thus, in the base scenario, it is appropriate to assume the current climate type in the region of the Olkiluoto site in the scenario formulation. Furthermore, Posiva judges that it is also appropriate to assume present-day characteristics regarding human habits, such as in respect of land use and demographic data.

Modelling of the impact of radionuclide releases to the surface environment following the formulation of relevant scenarios for consideration involves the following stages [Figure 5-8 of Posiva, 2012]:

- Projection of the development of the surface environment (the terrain and ecosystems are projected from their past development and surface and near-surface hydrological modelling is undertaken);[a]
- A screening analysis is undertaken using a stylized representation of the surface environment and highly cautious modelling assumptions to screen out radionuclides from further assessment;
- Landscape modelling is undertaken to provide a simplified representation of the surface environment in terms of hydrologically connected biosphere objects that are used with cautious radionuclide transport models to give time-dependent radionuclide concentrations in environmental media;
- A radiological impact assessment is performed based on maximal use of local resources.

These various stages are described in more detail below.

Development of the Surface Environment

The future development of the surface environment is assessed using Terrain and Ecosystems Development Modelling (TESM) and Surface and near-surface HYDrological modelling (SHYD). In the TESM, land-uplift-driven changes and other changes in the surface environment are simulated, until and beyond the time when the potential releases would reach it. The projections utilise identified typical succession lines for the development of sea bottom, shoreline, forests, mires, lakes, small water bodies and rivers. Humans are assumed to use the landscape based on the resources it may provide and on their needs, typically taking the most suitable resources first into use. This gives a link to the exposure pathways, which are assumed to reflect present human habits. The development modelling results in projections containing distinct biotopes, in which fauna find their habitats. Then, the food web or the structure of the biotic community can be outlined and representative species and their habits identified.

A sub-set of the projections produced by TESM are selected to be propagated to landscape modelling. The biosphere objects relevant to these projections are identified and characterised. As with SKB (Section A.3.3), a biosphere object describes a continuous and reasonably homogeneous segment of the modelled area that can potentially receive radionuclides released from the repository. The contamination can take place either by direct release of radionuclides from the repository through the geosphere or by horizontal transport of radionuclides within the surface environment during the biosphere assessment time window. Each biosphere object is characterised by one or more biotopes and a set of object-specific parameters. The biotypes can be divided to two main sub-groups, terrestrial and aquatic biotypes refined further to e.g., forest, cropland with varying products, rivers and open sea.

The SHYD model is a tool that can be used to study the water balance components at the Olkiluoto site. The model links the unsaturated and saturated soil water in the overburden and groundwater in the bedrock as a continuous pressure system. The fluxes for the biosphere assessment are calculated in two steps; first steady-state recharge/discharge to/from bedrock is computed for each time step and in the second step vertical and horizontal fluxes are computed for each delineated biosphere object. These fluxes are averages for the specific biosphere objects from the results of a full 3D-model. A new feature of the SHYD modelling compared with previous assessments is that anthropogenic (shallow)

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[a] The emphasis here is on the influence of the GBI on the upward transport of radionuclides from the geosphere to the biosphere, but it is also considered in terms of its influence on the geosphere within which the repository will be located. Indeed, beyond 10 ka, over repeated glacial cycles, the GBI is considered only to the extent that it may have effects on the repository.

wells are included; both those dug in the overburden and drilled in the bedrock can be added as sink points in the computational grid.

Screening Analysis

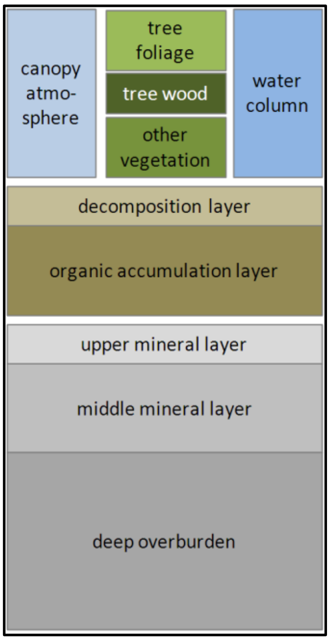
The screening analysis is of only limited relevance in the current context. A two-tier approach is adopted. In Tier 1, an extremely cautious approach is taken, in which it is assumed that a hypothetical individual is exposed, over one year, via inhalation, ingestion and external irradiation to the whole activity released out from the geosphere; integrated over the first 15 millennia after emplacement of the first canister, which is cautiously selected to 5 millennia beyond the period for which the radiation dose constraints apply. To estimate doses from ingestion and inhalation, it is assumed that the whole activity is incorporated by the exposed individual within one year. The effective committed annual doses (Sv) by ingestion and inhalation to an adult are calculated by multiplying this yearly intake (Bq) by the dose coefficients (Sv Bq^{-1}) for ingestion and inhalation, respectively. Doses from external irradiation (Sv) are calculated by assuming that the whole integrated release is deposited on a 1 m^2 surface. This conservatively estimated deposition density (Bq m^{-2}) is multiplied by the dose coefficient for external irradiation (Sv h^{-1} per Bq m^{-2}) and by assuming that the individual is exposed during the whole year the annual dose from external irradiation is obtained. The highest of these three annual doses, i.e. inhalation, ingestion and external irradiation, is used to calculate a risk quotient. If the risk quotient calculated for a specific radionuclide is greater than 1, then it is necessary to continue to Tier 2; otherwise this radionuclide is excluded from further more detailed analyses.

The model used in Tier 2 has a higher degree of realism than the straightforward Tier 1 analysis, but is still sufficiently cautious for screening purposes. It contains a set of mainly generic ecosystem-specific sub-models that may be used for determining through a simplified but conservative assessment the likely magnitude of the impact, and whether it can be neglected from further consideration or whether more detailed analysis is necessary. The sub-models in Tier 2 comprises a water well, a lake, a forest, an irrigated cropland and an irrigated pasture land. Exposure pathways considered are ingestion of radionuclides in water, milk, crops, livestock meat, game, mushrooms and berries, inhalation of radionuclides and external exposure from radionuclides in the ground. The screening decision for a specific radionuclide is based on the sub-model that generates the highest dose.

Landscape Modelling

The biosphere objects delineated in the surface environment development sub-process are used to construct the landscape model. Defining the initial state for the landscape model and how it develops with time is the landscape set-up activity, which is the task interfacing the surface environment development and the landscape modelling. In principle, a landscape model covering the whole area modelled in the surface environment modelling could be constructed. However, this is not necessary because it would result in a landscape model in which most of the biosphere objects would never receive any radionuclides. Hence, the approach is to limit the landscape model to only cover the area where the discharge locations to the surface environment are located, and areas potentially contaminated by radionuclide transport within the surface environment. The connections between the biosphere objects are derived from terrain projections for the period from the present (initial state) to the end of the dose assessment time window. These connections determine primarily how the biosphere objects are hydrologically connected, i.e. they determine if one object is upstream or downstream of another.

Each biotope in each biosphere object is associated with a deterministic radionuclide transport compartment model (see Figure A.19, left). One important feature of the landscape model is that it includes transitions over time from one biotope to another due to the development of the surface environment. It is thus crucial that the underlying radionuclide transport models are consistent on a conceptual level. In practice this means that it is important to ensure: 1) that the water fluxes between biosphere objects can be handled in a continuous manner, and 2) that the activity content of a specific compartment in a specific biotope can be transferred to a corresponding compartment when a biotope develops into another type, consistent with the knowledge on ecosystem succession. For practical implementation of the landscape modelling concept, the biosphere objects form aggregates which are called 'super-objects' (Figure A.19, right). The 'super-objects' are within landscape zones delineated so that their area does not change with the landscape development, i.e. the transport of radionuclides due to change of the ecosystem types is confined within the given zone. This facilitates the maintenance of mass balance in the model and prevents transitional effects on the occurrence of landscape changes.



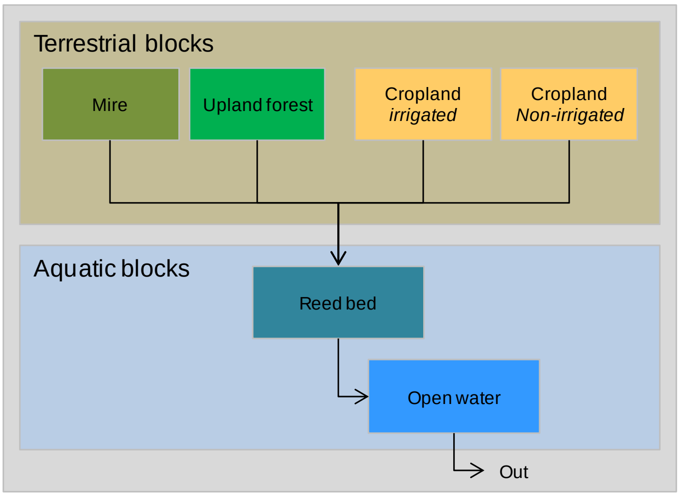


Figure A.19: Left: the Common Structure for Modelling any Biotope in any Ecosystem Type in a Biosphere Object. Right: The General Ecosystem Structure of 'Super-objects'. Figure 5-9 of Posiva [2012].

Each biosphere object comprises one, or a few connected, multi-compartment models, which in mathematical terms are systems of ordinary differential equations. The multi-compartment modelling approach uses transfer equations to model the fractional rate of transfer of activity between the modelled compartments.

Even though the compartment structure is common for all modelled ecosystem types, some ecosystem-specific features are implemented in the model. Aquatic objects lack the compartments *canopy atmosphere*, *tree foliage*, *tree wood* and *organic accumulation layer*. All forest and cropland objects lack the compartment *water column*; in addition: cropland used for pasture lacks the compartments *tree foliage* and *tree wood*, and cultivated croplands lack the compartments *tree foliage*, *tree wood*, *decomposition layer* and *organic accumulation layer*. This requires that a set of rules for how activity is transferred between the compartments is needed to address the situation in which objects develop from one ecosystem, or biotope, to another in the landscape model (see below).

A key assumption to be made in the modelling is to decide which compartment initially receives the activity released from the geosphere. In the reference case, it is assumed that the activity is introduced into the deep overburden compartment in all ecosystems.

The multi-compartment modelling approach above is applied to all radionuclides except C-14. The model for assessing exposure to releases of C-14 is based on the so-called specific activity approach, and is based on work by Avila and Pröhl [2008]. This approach has subsequently been updated, but is of marginal relevance in the current context and is not discussed further.

Although the modelling approach adopted by Posiva [2012] seems to differ in detail from the approach adopted by SKB (described in Section A.3.3), the methodology and structuring of biosphere objects appear to be very similar.

The main output of the landscape modelling sub-process is time-dependent radionuclide-specific spatial activity distributions in all biosphere objects for the analysed calculation cases. These are the key input to the radiological impact analysis.

Radiological Impact Assessment

In the radiological impact analysis, the spatially distributed, time-dependent radionuclide-specific activity concentrations in environmental media, produced by the landscape modelling, are used to calculate the potential radiological impact, in terms of annual effective doses to humans and absorbed dose rates to plants and animals. This part of the analysis uses standard approaches and is of little relevance to characterisation of the GBI, so it is not discussed further.

A.5 THE SAFETY CASE DEVELOPED BY ANDRA FOR DISPOSAL IN CLAY

A.5.1 Assessment Context

In France, the law of December 30, 1991 on the management of radioactive waste of high activity and with long life (HAVL), mentioned also in Article L.542 of the Environmental Code, entrusted to Andra the mission of evaluating the possibility of disposal of such waste in a major geological formation, in particular through the development of underground laboratories. Within this framework, research was undertaken on two types of geological medium: clay and granite. In 2005, Andra produced a report comprising a synthesis of the work of that they had undertaken on geological disposal in an argillaceous formation (work on granite had not been taken forward to the same extent). The law of December 1991 established a National Commission of Evaluation (CNE), an independent authority made up of French and foreign scientific experts, who examines the research undertaken by Andra and publishes each year an evaluation report. The law required that the Government should provide to the Parliament a report of evaluation of research, prepared by the CNE, in order to clarify the parliamentary debate in 2006. The report provided by Andra [2005] constituted an input to that debate. Although a substantial amount of work has been undertaken by Andra since that date, the 2005 report appears to be the most recent, publically available assessment report that can be cited. However, there are other useful documents that are available from Andra. For example, the following site description is taken in part from Volume 3 of the Andra internal document Plan General du Referentiel de Site [2009].

A.5.2 Geological Context

On 3 August 1999, the French Government authorised Andra to build a research laboratory with a view to studying the feasibility of deep geological disposal of high level and intermediate-level long-lived radioactive waste. The selected site is located in Bure, in the southern part of the Meuse district on the border of the Haute-Marne district.

The site is located in the eastern part of the Paris Basin within a zone of limestone plateaux at an altitude varying between 300 and 400 m above mean sea level. Outcrops of three rock formations appear over a 10-km radius around the site. Stretching from the south-east to the north-west, they consist of Kimmeridgian limestones and marls, Calcaires du Barrois Tithonian limestones, as well as Cretaceous rocks composed mainly of clay and sand [Plan General du Referentiel de Site, 2009].

Four streams (the Saulx, Orge, Ormançon and Ognon rivers) flow northwards in valleys partly filled with fine alluvial deposits. The ephemeral Bureau Brook starts at the Cité Spring, located close to the underground research laboratory, and flows into the Orge River [Plan General du Referentiel de Site, 2009].

In the area of interest, the landform comprises valleys that are deeply incised into a palaeosurface. Although the palaeosurface is ancient, much of the valley incision has occurred during the Quaternary and the maximum depth of incision of around 200 m implies an incision rate of around 100 m per million years. To a large extent, this incision can be attributed to adaptation of rivers to a base level that was typically about 80 m below present-day sea level throughout much of the Quaternary [Plan General du Referentiel de Site, 2009].

This substantial degree of recent incision has led to significant reorganisation of the drainage network, including river capture processes. It should be noted that the region lay beyond the maximum extent of the ice sheets during the Last Glaciation, but that periglacial features are observed (e.g. soil polygons and cryoturbation structures).

The 3D geological structure of the region is illustrated in Figure A.20 and a more detailed lithological sequence at the underground repository location is shown in Figure A.21.

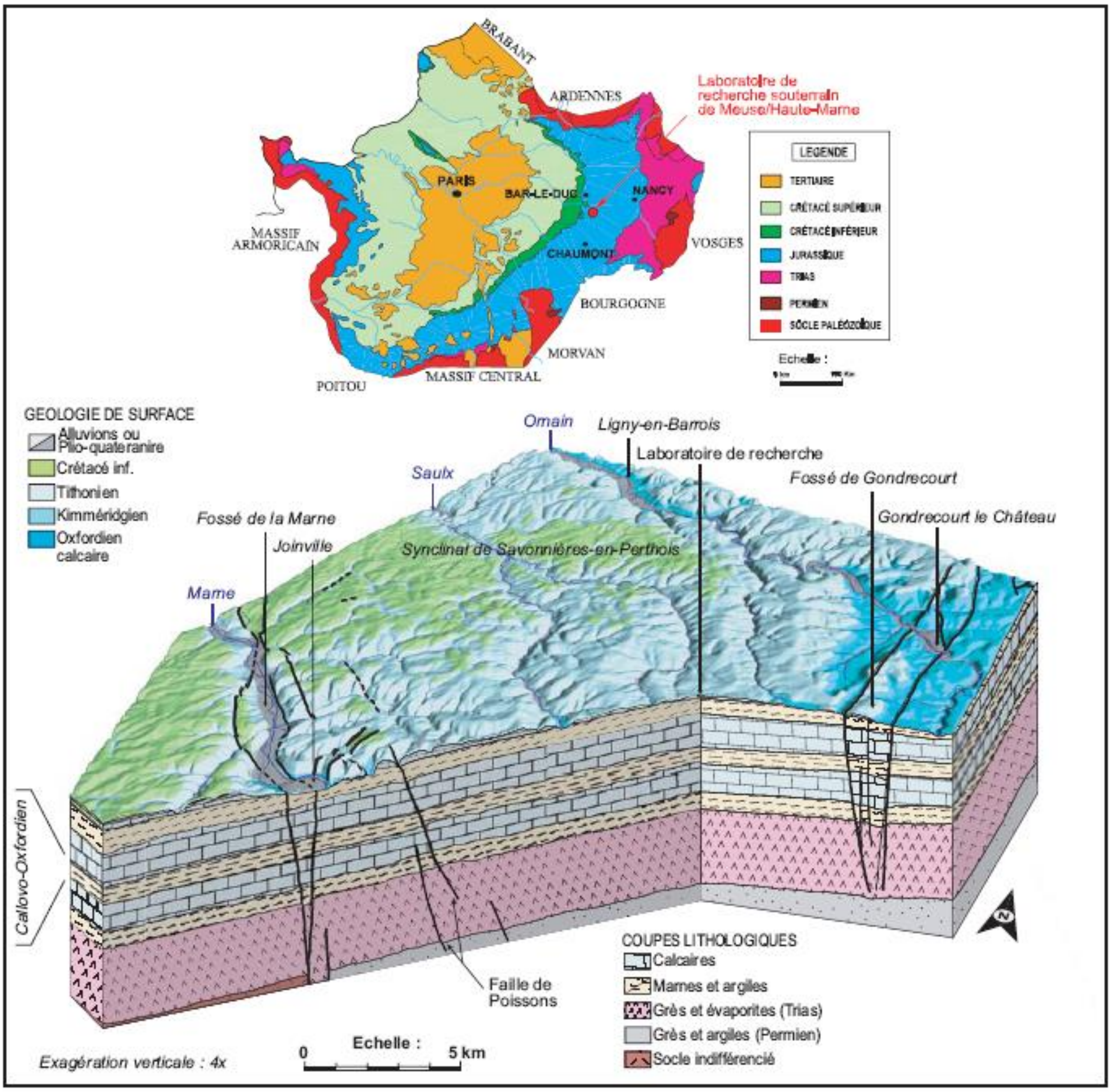


Figure A.20: Geological Structure of Bure Site (from Section 2.1.2 of the Andra [2005] Synthesis Report)

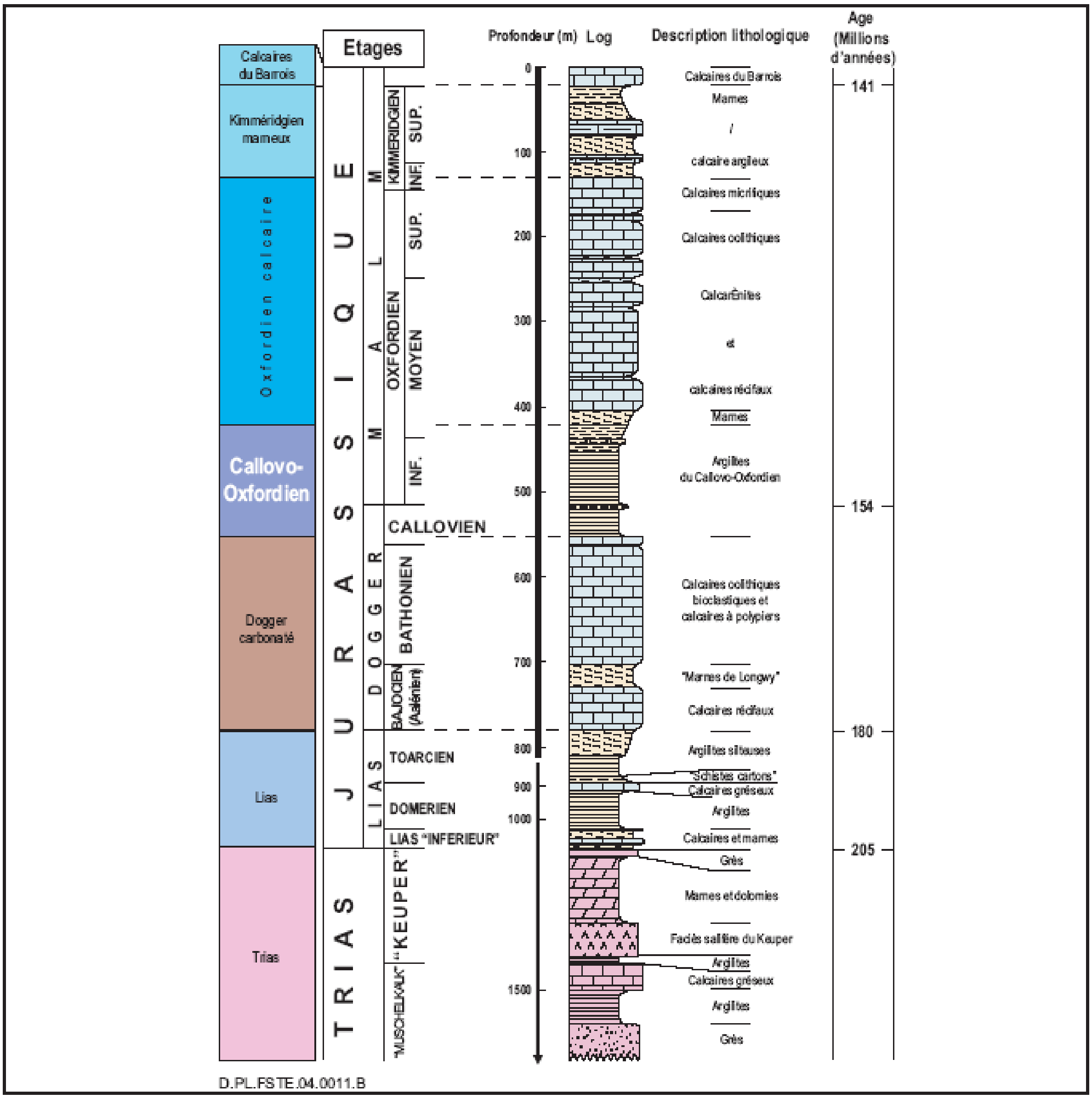


Figure A.21: Lithological Sequence at the Bure Underground Laboratory Location (from Section 2.1.2 of the Andra [2005] Synthesis Report)

It is proposed that the repository would be located in the Callovo-Oxfordian. The mudstones of Callovo-Oxfordian form a layer at between 422 and 552 m of depth at the underground laboratory location. With the dip of the layers towards the north-west, this depth increases gradually to reach more than 600 m at about 15 km north of the underground laboratory. In parallel, the thickness of the layer varies from 130 m to approximately 160 m from the south towards the north-west. The thickness of the layer and its homogeneity is a guarantee of good containment of radionuclide releases from the engineered system and transport is expected to be primarily by diffusion rather than advection.

Overall, Andra [2005] concluded that the Callovo-Oxfordian has properties in conformity with those needed for the implementation of a radioactive waste repository in an argillaceous medium. Specifically, the layer has a great thickness (130 m) and is not significantly affected by faults. Its geological history is well-known and it has been subject to little disturbance since its deposition, which constitutes a major argument for its homogeneity and its extreme stability. Additionally, it is not prone to seismic phenomena. The layer contains very little water and the displacement of that water is extremely slow, because of very low permeability of the layer. Physical and chemical characterization show, moreover, that it has a strong capacity to trap the major part of the chemical elements and radionuclides present in waste. It is suited to mining and the construction of the underground laboratory induced only of moderate disturbances which are not, *a priori*, likely to create preferential pathways of flow. There is a broad zone of more than 200 km^2 where these properties occur.

A.5.3 Characteristics of the Geosphere-Biosphere Interface

Radionuclides diffusing upward from the Callovo-Oxfordian would encounter a sequence of limestone aquifers and would be transported sub-horizontally in them, as well as diffusing vertically between them. The GBI is envisaged as including a well into one of these aquifers, with the water used for domestic and agricultural purposes. In addition, discharge into the riparian zone within an incised river valley is envisaged, as is upward transport from an unconfined contaminated aquifer to the rooting zone of plants (Figure A.22).

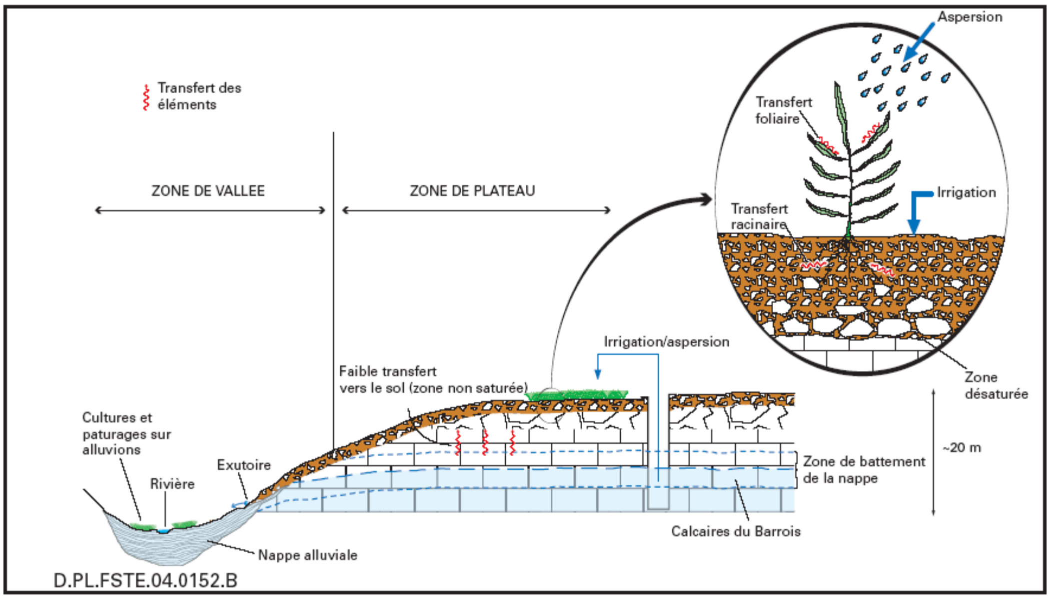


Figure A.22: The Geosphere-Biosphere Interface, as illustrated in Section 2.1.2 of the Andra [2005] Synthesis Report

A.6 THE SAFETY CASE FOR OPG'S DEEP GEOLOGICAL REPOSITORY FOR LOW AND INTERMEDIATE LEVEL WASTES

A.6.1 Assessment Context

Ontario Power Generation (OPG) is proposing to build a Deep Geologic Repository (DGR) for low and intermediate level waste (L&ILW) near the existing Western Waste Management Facility (WWMF) at the Bruce nuclear site in the Municipality of Kincardine, Ontario (Figure A.23). The Nuclear Waste Management Organization (NWMO), on behalf of OPG, has prepared an Environmental Impact Statement (EIS) and Preliminary Safety Report (PSR) for a site preparation and construction license for the proposed repository. These are currently under regulatory review.

The project involves investigation of the site's geological and surface environmental characteristics, conceptual design of the DGR, and safety assessment. The Version 2 post-closure safety assessment evaluates the long-term safety of the proposed facility and provides support for the EIS and PSR [OPG, 2011].

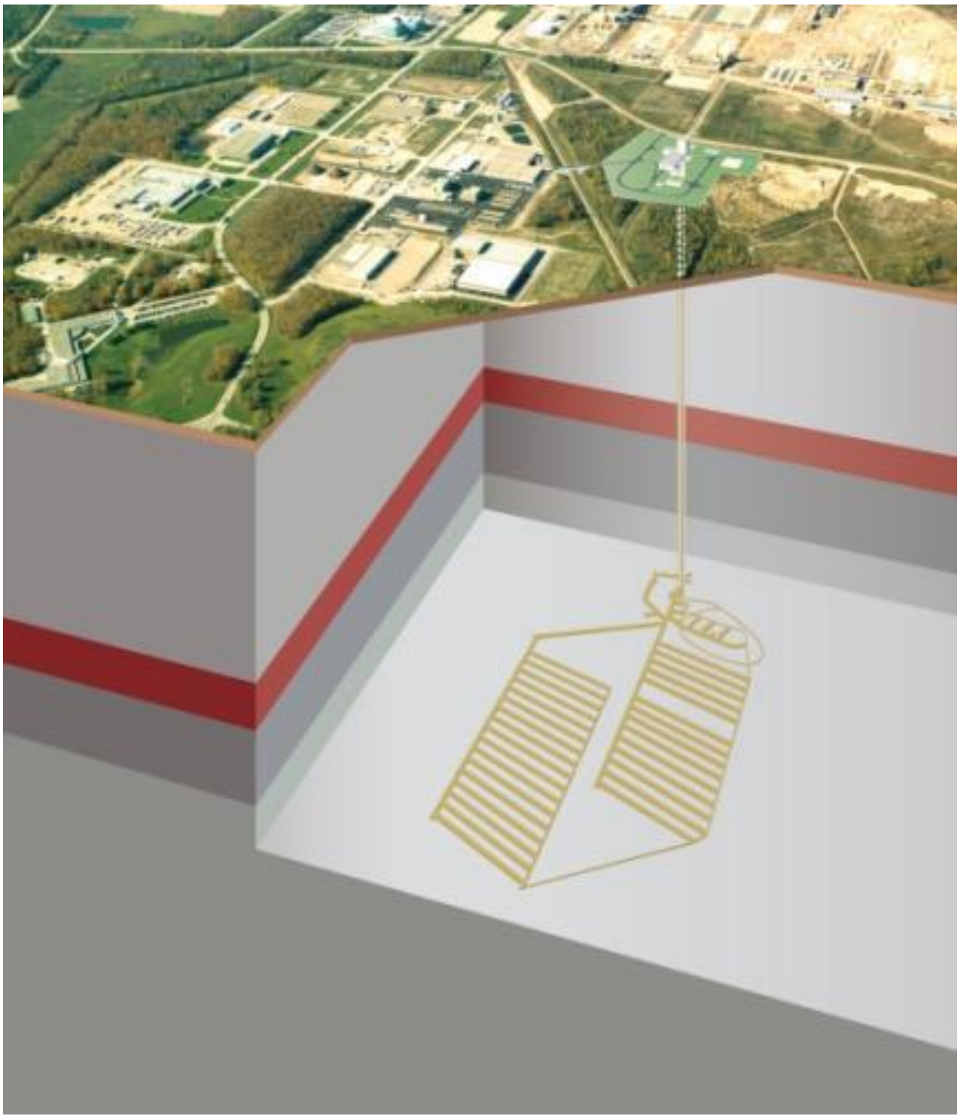


Figure A.23: The Proposed Deep Geologic Facility at the Bruce Site, Ontario [OPG, 2011]

The DGR will accept operational and refurbishment L&ILW from OPG-owned nuclear power plants. However, OPG is not seeking a licence to emplace decommissioning waste in the DGR. The DGR will not accept used nuclear fuel.

Certain wastes will be conditioned prior to being sent to the DGR. The main waste conditioning practices undertaken by OPG are incineration (resulting in the generation of the bottom ash and bag-house ash) and compaction (resulting in the generation of compacted waste bales and boxes). In addition, the assessment assumes that steam generators from the planned refurbishment programmes will be filled with grout and cut into smaller sizes. In addition, some LLW has historically been conditioned by other methods, such as grouting with cement, immobilisation with bitumen, and the addition of polymeric absorbers. Cementitious grout has been or will be added to some ILW to provide mechanical support for waste retrieval and handling rather than as a waste conditioning agent. The proportion of wastes that has been/will be subject to such waste conditioning is small.

A wide range of packages is proposed to dispose of these various types of waste [see Section 2.1 of NWMO, 2011a]. The total volumes to be disposed are 163,000 m^3 of LLW and 41,000 m^3 of ILW (note that these are disposed volumes rather than raw waste volumes).

The reference depth for the repository floor is 680 m below ground surface in competent and tight limestone (the Cobourg Formation). The repository comprises two shafts, a service area, two access tunnels leading to two panels comprising 31 rooms in total, and a return air drift.

A.6.2 Geological Context

The proposed repository location is on the eastern edge of the Michigan Basin (Figure A.24). The Michigan Basin is a ‘bulls-eye’ basin, filled with over 4 km thickness of Palaeozoic sedimentary rocks that gently dip towards the centre of the basin. The basement comprises Precambrian granitic gneiss. The Palaeozoic sedimentary sequence comprises Cambrian sandstones overlain by Ordovician, Silurian and Devonian limestones, shales, dolostones and dolomitic limestones and evaporites. Figure A.25 shows a cross-section through the Michigan basin.

The rocks forming the eastern side of the basin have been folded along a southwest to northeast axis, forming the Algonquin Arch. The arch existed as a basement high during deposition of Cambrian sediments and persisted throughout most of the Palaeozoic Era. The arch acted as a major structural control on depositional patterns, rising and falling with respect to the Michigan and Appalachian basins in response to vertical epeirogenic movements and horizontal tectonic forces [NWMO, 2011a; 2011c]. This structural control resulted in thinning, pinch-outs, and erosional truncation of stratigraphic units as they approach and pass over the arch. Where the Algonquin Arch meets the northerly trending Findlay Arch there is a structural depression known as the Chatham sag. To the northeast the Frontenac Arch forms the pinch-out margin of the sedimentary section of Southwestern Ontario. The DGR site is located within the Bruce Megablock, a structural domain identified within the sedimentary sequence overlying the Precambrian basement. The Bruce Megablock is bounded to the west by the Grenville Front Tectonic Zone (GFTZ), the Niagara Megablock to the south, and the Georgian Bay Linear Zone to the east. The GFTZ has been tectonically stable for the last 1000 Ma, and therefore has not affected the deposition or structure of the overlying younger Palaeozoic rocks [NWMO, 2011a; 2011c].

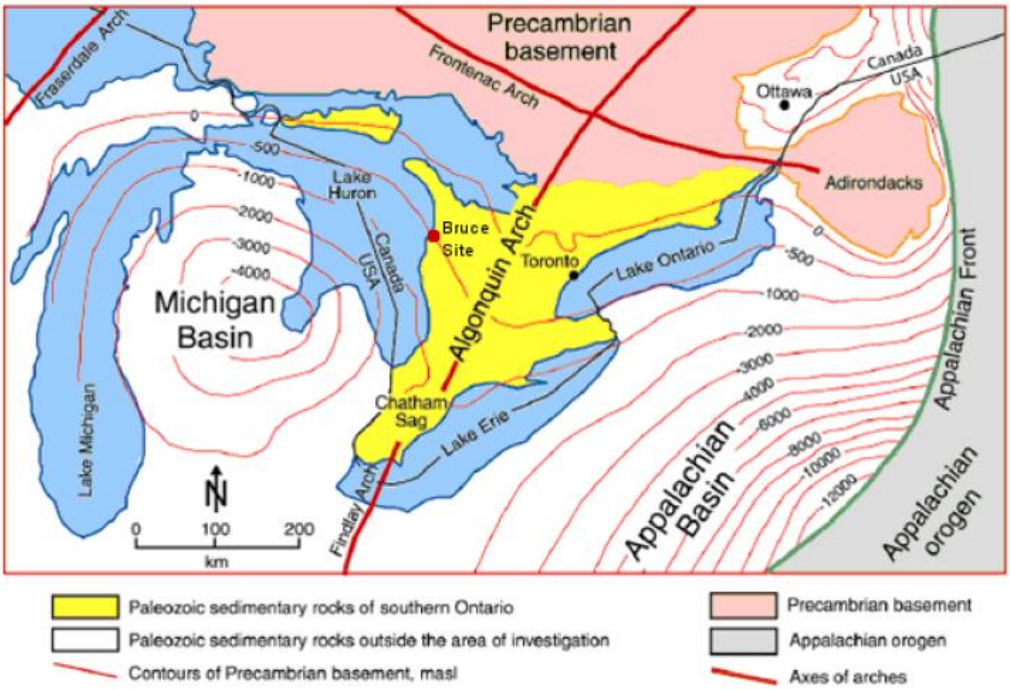


Figure A.24: Location of the Bruce Site toward the edge of the Michigan Basin

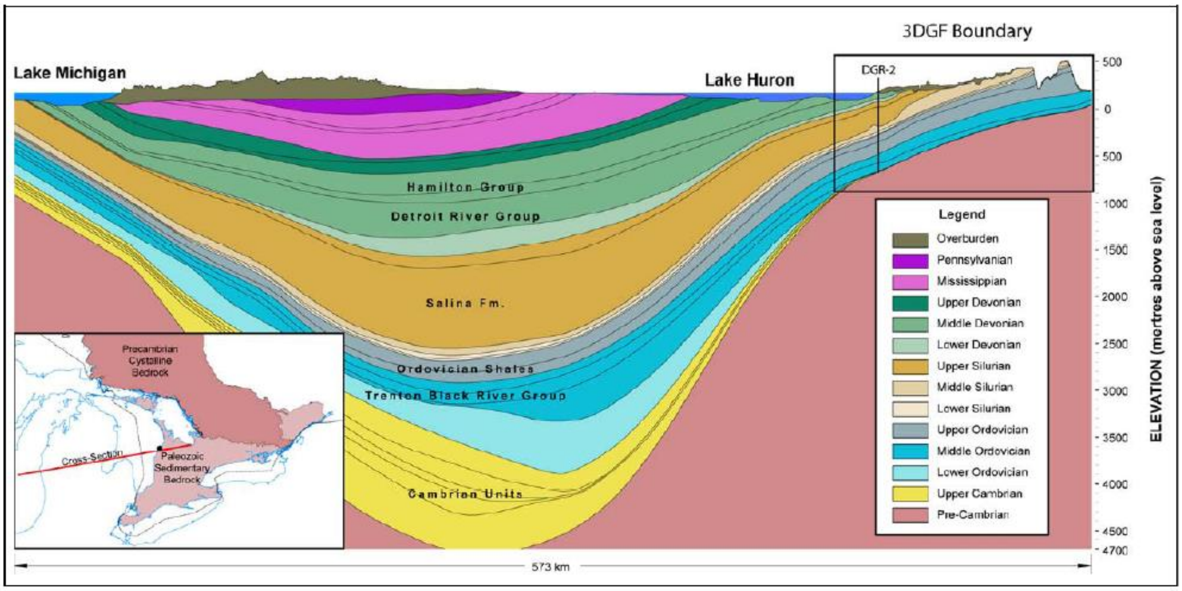


Figure A.25: Vertically exaggerated cross-section across the Michigan Basin [NWMO, 2011a; 2011c] (The DGR-2 borehole at the Bruce site and the boundary of the 3D Geological Framework model are marked)

The Palaeozoic bedrock sequence overlying Precambrian granitic basement has been measured to be over 800 m thick in the DGR site investigation boreholes [NWMO, 2011a; 2011c]. It comprises (from top to bottom):

- c.105 m of Devonian dolostones (dolomitic limestones);
- c.325 m of Silurian dolostones and shales;
- c.400 m of Ordovician shales and argillaceous to shaley limestone;
- c.15 m of Cambrian sandstone overlying Precambrian granitic gneiss.

Unconsolidated ('overburden') sediments overlie this bedrock sequence. These sediments are comprised of a comparatively complex sequence of Quaternary surface sands and gravels from former beach deposits (associated with Lake Huron) overlying clayey-silt to sandy silt till of glacial origin with interbedded lenses and layers of sand of variable thickness and lateral extent. The total thickness of this overburden varies from less than 1 m along the shore of Lake Huron to a maximum of about 20 m above the DGR site.

A hydrogeological conceptual model has been developed for Southwestern Ontario. The conceptual model formed the basis for regional-scale groundwater modelling within a portion of Southwestern Ontario centred on the DGR site. Three groundwater domains are identified in this model: a shallow zone characterised by Devonian-aged formations which have a higher permeability and contain groundwaters with a relatively low Total Dissolved Solids (TDS) content; an intermediate zone which consists of Silurian formations, including low permeability shales and evaporite units in which the TDS content increases with depth; and a deep groundwater zone within the Ordovician shales and limestones, Cambrian sandstones (where present), and the Precambrian basement with a high TDS content. (Note that the Cambrian sandstones are discontinuous and pinch-out against the Precambrian basement.) The superficial aquifer system represented by unconfined, semi-confined and confined aquifers present in the Quaternary glacial drift sediments can also be considered to be part of the shallow flow system in the regional model [NWMO, 2011a]. In general, modern recharge infiltrates topographic highs, such as glacial moraines and the spine of the Algonquin Arch, and migrates through glacial drift and shallow bedrock aquifers, to ultimately discharge into topographic lows, such as streams and lakes. Modern groundwater flow in the Great Lakes region is primarily restricted to the shallow unconfined glacial drift aquifers [NWMO, 2011a].

The direction of groundwater flow in the shallow Devonian bedrock and glacial aquifers is gravity-driven and topographically controlled. However, the low topographic gradients and high salinity of underlying basin formation waters prevent deep circulation of meteoric waters. In the intermediate and deep groundwater zones, the only potential location for groundwater recharge or discharge is along the bands along which these formations outcrop. Fresh water infiltrating into these zones is likely to have a major component of flow parallel to the strike of the formations because i) the densities of the shallow waters in the bedrock are substantially higher than that of fresh water and they are therefore not easily displaced; ii) the absence of discharge areas in the basin, and therefore very low hydraulic gradients; and iii) the hydraulic conductivity rapidly decreases at the base of the shallow system.

At the local or site-scale, the same groundwater zones are considered as in the regional model, except that the surficial groundwater zone is explicitly considered. Thus, the zones are the following.

The Surficial Deposits (Overburden) Groundwater Zone: The overburden sediments in which fresh water enters the groundwater system from precipitation through the recharge zone and flows vertically downwards into the underlying Shallow Bedrock Groundwater Zone. Layers of sand and gravel constitute local aquifers whereas the till layers comprise aquitards.

The Shallow Bedrock Groundwater Zone: The Devonian and Upper Silurian dolostone sequence of the Lucas, Amherstburg, Bois Blanc and Bass Islands Formations and the top of the Salina Formation (Salina G). The direction of groundwater flow is westward to a point of near-shore discharge in Lake Huron.

The Intermediate Bedrock Groundwater Zone: This includes the dolostone and shale sequence of the Salina, Guelph, Goat Island, Gasport, Lions Head, Fossil Hill, Cabot Head and Manitoulin Formations. The formations are dominantly of low permeability, movement of pore water is very slow and mass transport is considered to be diffusion dominated. However the Guelph and Salina A1 evaporite are relatively more permeable. Total dissolved solids (TDS) increases with depth through the zone.

The Deep Bedrock Groundwater Zone: This is associated with the low permeability Ordovician shales and limestones and the underlying Cambrian sandstones and Precambrian granitic gneiss. Within the sediments, movement of pore water is very slow and mass transport is considered to be diffusion dominated.

As noted above, the repository is located in the Deep Bedrock Groundwater Zone at a depth of 680 m within the Cobourg Formation (argillaceous limestone). Groundwater flow within the surficial deposits and bedrock of the area around the DGR site is directed generally north-westward toward Lake Huron, generally sub-parallel to the well-established surface drainage pattern shown in Figure A.26. The groundwater levels in the bedrock beneath the Western Waste Management Facility (WWMF) on the Bruce Site occur between about 8 m to 10 m below ground surface. The bedrock water levels (i.e., those in the Shallow Bedrock Groundwater Zone) rise to levels above the bedrock indicating artesian conditions with respect to the bedrock surface.

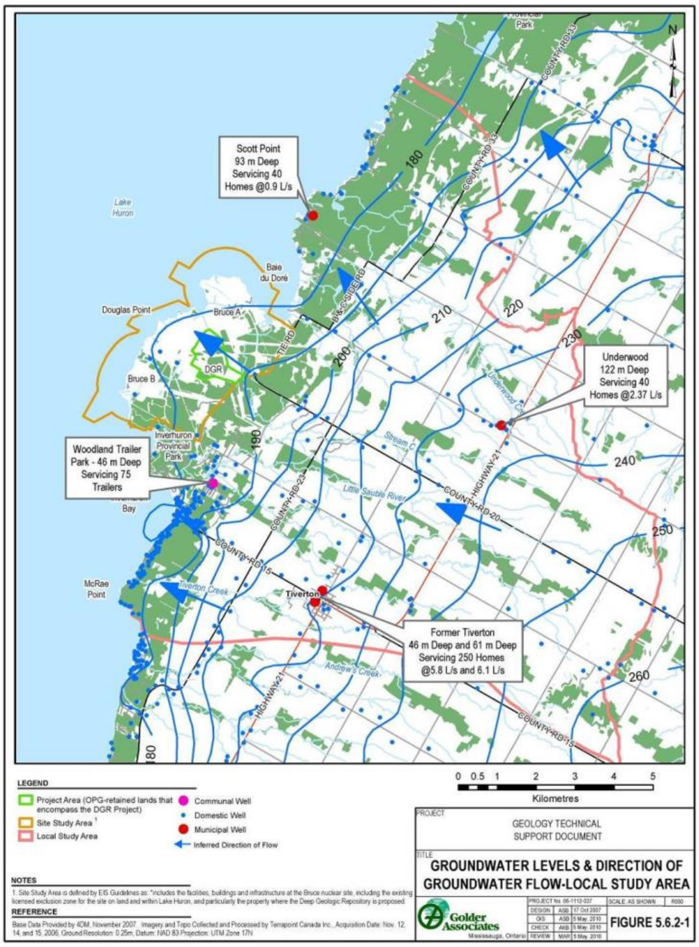


Figure A.26: Groundwater Levels (mASL) and Direction of Shallow Groundwater Flow in the Regional Study Area [NWMO, 2011a]

Geochemical evidence indicates that glacial or younger recharge is most often identified in shallow (<130 m) environments. Some deposits of lower-permeability till contain water of glacial age that was trapped when the sediments were deposited. Salinity and hence the groundwater age increases with depth in the Shallow Bedrock Groundwater Zone. (Salinity continues to increase from the base of the Shallow Bedrock Groundwater Zone, through the Intermediate Bedrock Groundwater Zone, to the top of the Deep Bedrock Groundwater Zone.) Based on geochemical evidence, the porewaters in the deep and intermediate zones are considered to be very old, confirming the stability of these zones, consistent with their very low hydraulic conductivities. From this evidence, it has been inferred that the brines in the deep and intermediate zones are 250 million years old.

The majority of the formations within the Intermediate and Deep Bedrock Groundwater Zones have very low hydraulic conductivities and, therefore, advective flows are negligible. Consequently, any solute transport will be diffusion dominated. This is confirmed by water chemistry data. The only exceptions to this are within the Cambrian, Guelph and Salina A1 Upper Carbonate formations.

The Cambrian formation is located below the repository and is associated with a high excess hydraulic head. The horizontal hydraulic gradient in the Cambrian is very low, and there is not expected to be any flow from the Cambrian to the biosphere. This is because the Cambrian formation pinches out against the Precambrian basement and is overlain by the low permeability Ordovician and younger rocks. Results from the regional groundwater flow model for the Michigan Basin indicate that this head is density driven. The head is not evolving and will be stable for the timescales considered in the assessment.

The Guelph and Salina A1 Upper Carbonate formations are located above the DGR. Even though they are of relatively high hydraulic conductivity, there is limited flow in these formations at the DGR site. This is because they lie between overlying and underlying low permeability formations, and the associated hydraulic gradients are low. The hydraulic gradient in the Salina A1 Upper Carbonate formation is consistent with topographically driven strike-parallel flow, resulting in discharge to Lake Huron where the formation sub-crops to the northwest of the DGR (Figure A.27). Due to the subdued topography, the hydraulic gradient is low and the pathline is long (tens of kilometres) resulting in very long travel times. The hydraulic gradient in the Guelph is not strike parallel, and is oriented toward the north-east [NWMO, 2011a].

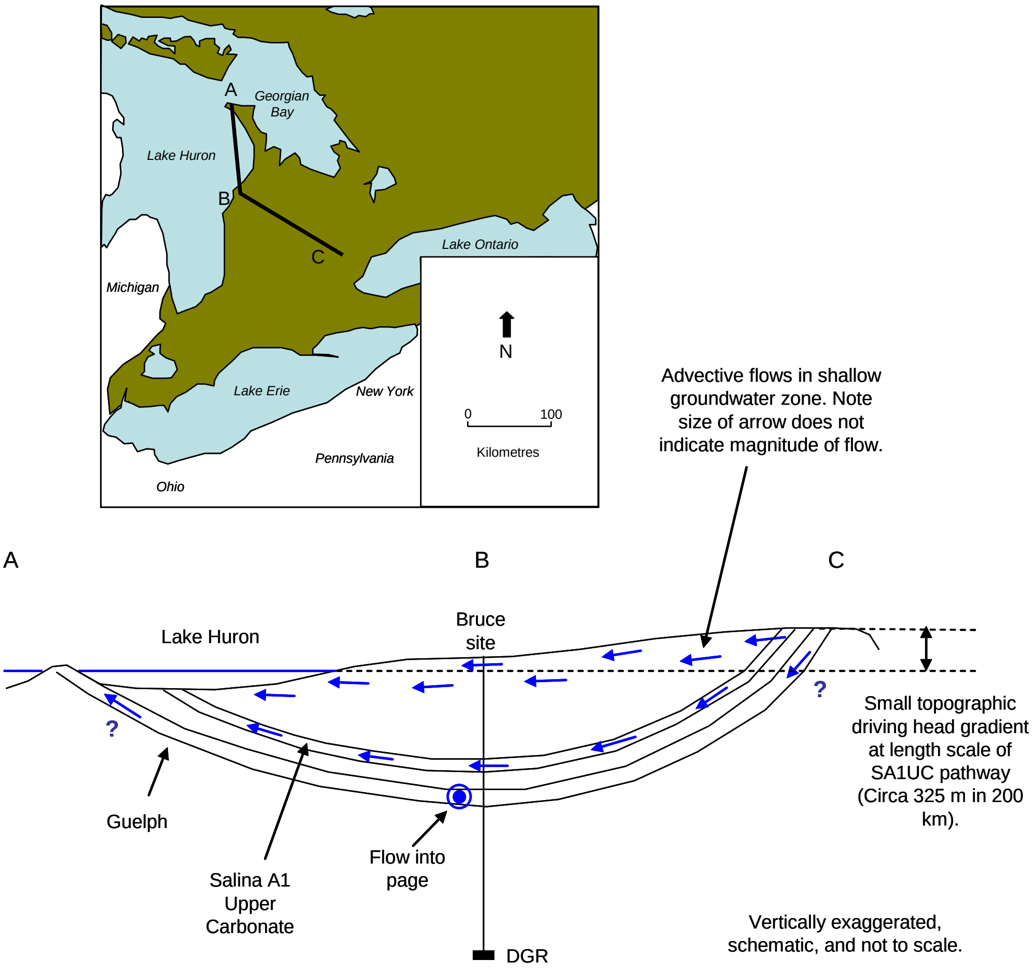


Figure A.27: Hypothetical Groundwater Flow Paths above the Proposed DGR Location (NWMO, 2011a)

A.6.3 Environmental Change and the Geosphere-Biosphere Interface

From a consideration of the long-term processes of environmental change operating at the Bruce site, NWMO [20011a] has developed the following illustrative description of the evolution of the biosphere system through a series of stylised biosphere states for consideration in the current safety assessment.

Following closure of the repository, controls will remain effective for a period of at least 300 years. However, once controls are no longer effective, land uses will become consistent with the present-day practices in the wider region. Although the DGR system will be affected by global warming in the short term (i.e., on the scale of centuries or perhaps a thousand years), the associated changes will not be significant from the perspective of the post-closure safety assessment since they will not modify the fundamental nature of the biosphere system and its processes. However, global warming will mean that the onset of the next glacial cycle is likely to be delayed, and the next ice-sheet coverage of the site would not occur for at least 60,000 years. Following the onset of climatic cooling, the climate will become drier and the present-day temperate ecosystem will gradually evolve into a tundra ecosystem characterised by sparse vegetation such as lichens, grasses, sedges and arctic-adapted low-lying plants, and dwarf shrubs and discontinuous permafrost. The timescale over which this evolution will occur is uncertain, but previous work for a slightly more northerly latitude has suggest that it could be up to a few thousands of years. This tundra period is likely to be the predominant biosphere state during a glacial cycle.

With further cooling, the land surface temperature will fluctuate around the freezing point, but eventually the average annual surface temperature will drop below 0°C, and snow will begin to accumulate without melting. An ice-sheet will start to advance over the site, developing to a maximum thickness of 3 km. Where the ice and snow provide adequate insulation against heat loss from the earth's interior, the interface between the ice and the underlying solid earth will reach temperatures that are at or slightly below freezing. Towards the end of the glacial cycle, the ice-sheet will start to retreat relatively rapidly by melting, resulting in voluminous discharges of meltwater. Regionally, this will be likely to lead to the formation of large proglacial lakes, erosion of poorly resistant rocks and sediments in some locations, and deposition of thick layers of glacially derived sediments elsewhere. Subsequently, further warming will result initially in the re-establishment of tundra conditions, and the eventual warming to present-day temperatures resulting in the re-establishment of a temperate ecosystem. Based on historical records, the warm conditions will persist for about 20,000 years until another cooling period initiates the next cycle of glaciation. This new cycle of glaciation will have a different behaviour in detail, due in part to the different solar insolation variations in the future. However, NWMO [2011a] considers that it is sufficient to model it based on the previous historic cycle including its three glacial maxima, as this cycle includes the key aspects of a glacial cycle. This results in the following sequence of biosphere states: temperate => tundra => glacial => post-glacial => tundra => glacial => post-glacial => tundra => glacial => post-glacial => tundra => temperate. For assessment purposes, this sequence of glacial/interglacial cycling is repeated for the remainder of the assessment timeframe with a periodicity of around 100,000 to 120,000 years, consistent with historic records over the Late Quaternary.

From the above description of the evolution of the biosphere, four biosphere states were identified: temperate, tundra, glacial and post-glacial. Each state was defined to represent a configuration of the system that is reasonably likely to occur during the evolution of the biosphere, and is of interest in relation to assessing the safety of the DGR system [NWMO, 2011a]. Schematic illustrations of these four states are shown in Figure A.28.

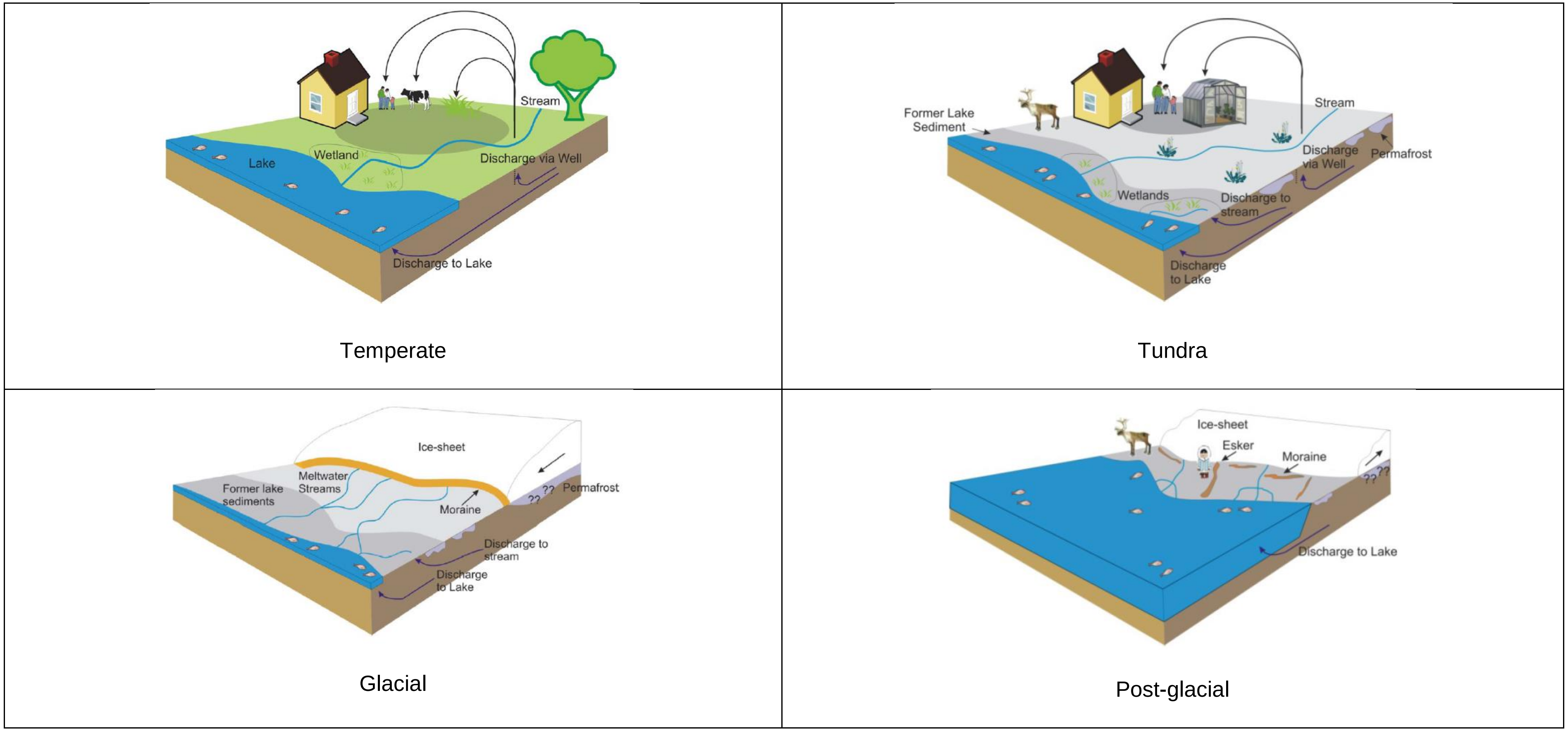


Figure A.28: Biosphere States showing the Geosphere-Biosphere Interfaces (NWMO, 2011a)

In the temperate state, the characteristics of the soils, surface waters and biota are similar to the present day. Human habits are the same as at the present day, with the land being used for agricultural and recreational purposes. Groundwater discharges to the lake and could be pumped from a well in the Shallow Bedrock Groundwater Zone. Well-water is used for agricultural and domestic purposes. Wetlands and other natural environments are sources of wild food.

In the tundra state, the lake may retreat as a result of reduced precipitation, exposing former lake sediments. Other soils may become peaty in nature due to the slow decomposition of organic matter in the cold climate. Any permafrost that might be present would be discontinuous and limited to less than a few tens of metres. The types of biota that are present are comparable with the biota found in present-day tundra environments. Human habitation is be expected to continue to be feasible, but reduced temperatures and precipitation means that agriculture is limited to growing of crops under cover and there is greater reliance on subsistence hunting, fishing, and trapping. Groundwater continues to discharge to the lake and the retreat of the lake may lead to some limited discharge of water from the Shallow Bedrock Groundwater Zone to a stream. Although there is likely to be reduced demand for water (due to reduced agricultural activity), it is likely that water will continue to be pumped from a well in the Shallow Bedrock Groundwater Zone.

In the glacial state, the ice-sheet will approach and pre-glacial effects will become evident and the biota more limited. The lake may also continue to retreat due to reduced precipitation, exposing sediments. However, this retreat could be mitigated by meltwater coming from a warm-based ice-sheet, especially if other lobes of the ice-sheet cut off the water outlet. As the ice-sheet advances sediments will be eroded due to the action of the ice and meltwater, and moraines (accumulations of unconsolidated soil and rock) will develop at the front of the ice-sheet. Groundwater releases are expected to continue to the lake basin and also potentially to other surface waters that may form in advance of the ice-sheet (if warm-based). Permafrost might continue to develop, but it is likely to remain discontinuous and is unlikely to extend to a depth in excess of 60 m. If the ice-sheet is warm-based, the permafrost is likely to disappear as the ice-sheet advances over the site. Recharge to the shallow groundwater will decrease if the ice-sheet is cold-based, and increase if it is warm-based. Self-sufficient permanent human habitation in the region is very unlikely as the environment will be harsh and inhospitable, especially once the site has been overrun by the ice-sheet. Prior to the site being overrun by the ice-sheet, there might be some limited use of resources in the region (e.g., the lake) by temporary visitors (e.g. fishermen, nomadic people).

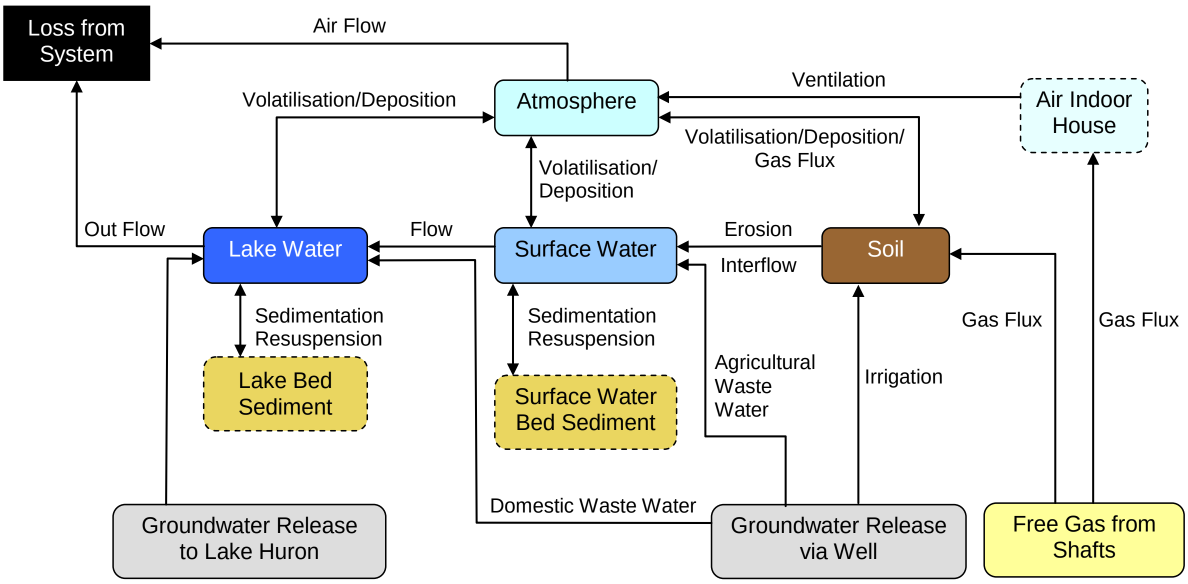
In the post-glacial state, the DGR site is likely to be covered by a proglacial lake. This would follow the retreat of the ice sheet from the site, but also, more generally, reflects the expanding lake size as it collects meltwater from a more distant, retreating ice sheet. Eventually, the Proglacial Lake is expected to overlie the site completely, before gradually receding as a result of ameliorating climatic conditions, drainage and isostatic rebound. The landscape in the vicinity of a retreating ice sheet will consist primarily of sands, clays and gravels, and exposed bedrock; there will be little soil development. Some nomadic animals, e.g. herds of caribou and flocks of migratory birds, will be present and vegetation will be limited to a few hardy species. There could be a transient presence of people who make use of local resources, especially fish.

Overall, taking all four of the biosphere states into account, the following types of GBI are envisaged:

- groundwater discharge via the Shallow Bedrock Groundwater Zone into a lake;
- groundwater wells near the repository in the Shallow Bedrock Groundwater Zone;
- gaseous releases into the atmosphere above the repository, primarily focussed around the Main and Ventilation Shafts;
- groundwater discharge via the Shallow Bedrock Groundwater Zone into a stream/river;
- groundwater discharge via the Shallow Bedrock Groundwater Zone into a marsh;
- groundwater discharge via the Shallow Bedrock Groundwater Zone to a lake shore.

The first three of these GBIs apply to temperate conditions, whereas the latter three apply in future cooler environments.

In practice, in the assessment of the normal evolution scenario, rather than explicitly representing the evolution of glacial climate, the model adopted considered stylised, constant temperate conditions that are comparable with those presently found at the site. This was expected to provide a useful indicator of potential impact, even on long time scales. The potential impact of a tundra climate was also considered to illustrate the potential impact of a different climate condition [NWMO, 2011b]. The conceptual model adopted for radionuclide transport in the biosphere for a radionuclide release in groundwater, including the GBI, is illustrated in Figure A.29.



Note: Dotted borders indicate components treated in equilibrium.

Figure A.29: Conceptual Model of Biosphere Contaminant Migration Processes for Groundwater Releases [NWMO, 2011b]

A.7 THE APPROACH TO BIOSPHERE ASSESSMENT ADOPTED BY NAGRA

A.7.1 Assessment Context

According to the Swiss nuclear energy legislation, responsibility for radioactive waste management lies with the waste producers. Therefore, in 1972, the operators of the nuclear power plants and the Swiss Confederation (responsible for radioactive waste from medicine, industry and research) established the National Cooperative for the Disposal of Radioactive Waste (Nagra – Nationale Genossenschaft für die Lagerung radioaktiver Abfälle) to implement permanent and safe disposal of all types of radioactive waste generated in Switzerland.

The members of the Nagra Cooperative are:

- Swiss Confederation (represented by the Department of Home Affairs)
- BKW FMB Energie AG, Bern (Mühleberg NPP)
- Kernkraftwerk Gösgen-Däniken AG, Däniken (Gösgen NPP)
- Kernkraftwerk Leibstadt AG, Leibstadt (Leibstadt NPP)
- Axpo AG, Baden (Beznau I and II NPPs)
- Alpiq Suisse SA, Lausanne
- Zwilag Zwischenlager Würenlingen AG, Würenlingen

The Nuclear Energy Act [2003] requires disposal of all types of radioactive waste in geological repositories. Current planning foresees a repository for spent fuel, vitrified high-level waste and long-lived intermediate waste (HLW repository) and a repository for low- and intermediate-level waste (L/ILW repository); the possibility of a "combined" repository is also considered. The repositories will be built at a depth of several hundred meters in suitable rock formations. Depending on the type of waste to be emplaced, they will consist of disposal tunnels or caverns, a pilot facility for monitoring a representative sample of the waste, a test facility (rock laboratory), surface installations and access tunnels or shafts.

Nagra requires a capability to assess potential radiological exposures in the biosphere for comparison against dose targets, should radionuclides be released from a repository and migrate to the surface environment over long periods of time post-closure. Currently, such dose assessments are undertaken using the Swiss Biosphere Assessment Code, SwiBAC. The conceptual and mathematical basis for Nagra's biosphere assessment model, which SwiBAC implements, is given by Walke [2012].

A.7.2 Geological Context

The nuclear energy legislation specifies that the site selection process for the L/ILW and the HLW repositories should be governed by a so-called "sectoral plan" – a stepwise decision-making approach within the framework of the spatial planning legislation. The 'Sectoral Plan for Deep Geological Repositories' [2008] defines the site selection criteria, the role of the various stakeholders as well as the three stages of the process. Site selection is based primarily on scientific and technical criteria, with the main emphasis on safety, but socio-economic and environmental aspects must also be addressed. The sectoral plan process is led by the Swiss Federal Office of Energy.

In Stage 1 (2008 – 2011), six potential geological regions were identified – Südranden, Zürich Nordost, North of Lägern, Jura Ost, Jura-Südfuss and Wellenberg (Figure A.30). All have clay-rich sediments as a potential host rock. The proposals were reviewed by the authorities, submitted to a broad consultation and finally approved by the Federal Council on 30 November 2011.

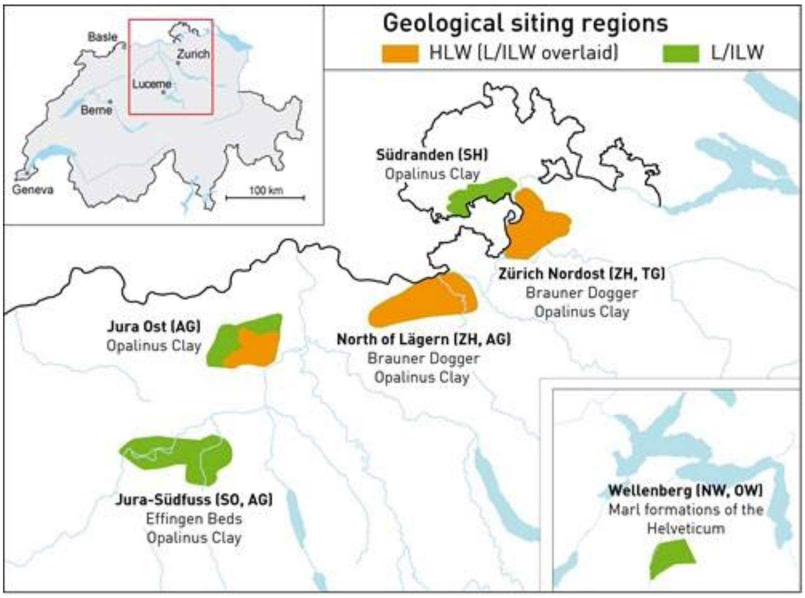


Figure A.30: The siting regions (cantons in brackets) and the respective host rocks, as proposed in Nagra Technical Report NTB 08-03 [2008], see www.nagra.ch

The goal of Stage 2, now ongoing, is the selection of at least two potential sites for each type of repository within the siting regions identified at Stage 1. This includes both the sites for the underground facilities and the location of the required surface infrastructure. To this aim, Nagra has carried out provisional safety analyses that will form the basis of the safety-based comparison of the sites. Another key component of Stage 2 is regional participation, which gives representatives from the siting regions the opportunity to have their interests and concerns taken into account. Nagra's proposals for Stage 2 are foreseen to be published early in 2015 and the decision of the Federal Council is expected in 2017. In Stage 3, the remaining siting regions will be investigated in depth and narrowed down to a single siting region per repository type (or a single site for a combined repository) and will result in a general licence application.

A.7.3 The Geosphere-Biosphere Interface in SwiBAC

SwiBAC represents both water and solid fluxes between different components of the environment. The water fluxes are illustrated in Figure A.31 and the solid mass fluxes in Figure A.32.

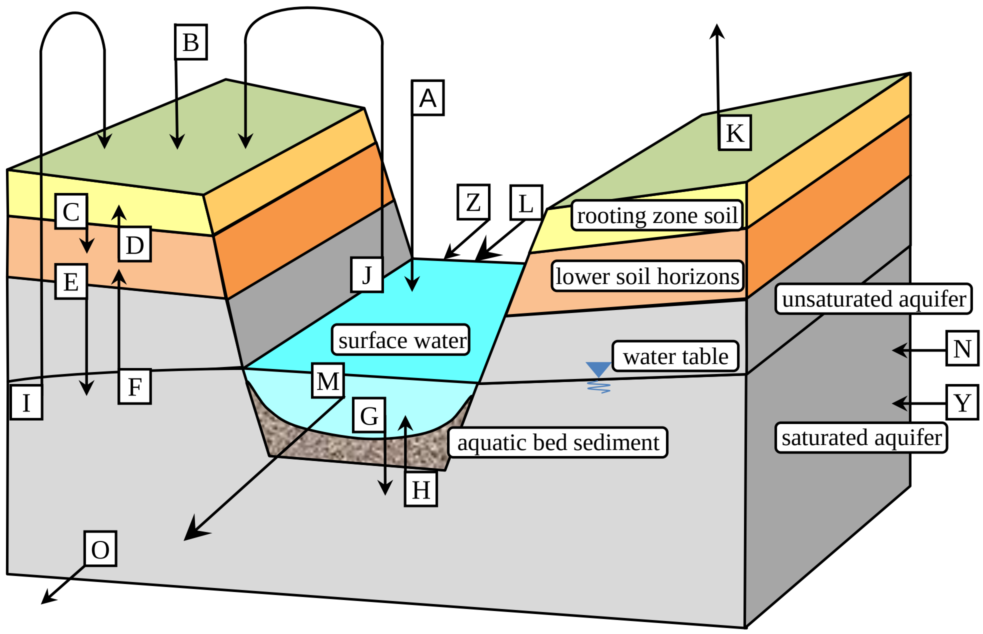


Figure A.31: Conceptualisation of the Principal Water Fluxes in SwiBAC [Walke, 2012]

Nomenclature:

A	Precipitation: → water surface
B	Precipitation: → soil surface
C	Infiltration: rooting zone soil → lower soils
D	Upward movement: lower soils → rooting zone soil
E	Infiltration: lower soils → near-surface aquifer
F	Upward movement: near-surface aquifer → lower soils
G	Infiltration: surface water → near-surface aquifer (via bed sediment)
H	Discharge: near-surface aquifer → surface water (via bed sediment)
I	Irrigation with groundwater
J	Irrigation with surface water
K	Evapotranspiration: evaporation loss to atmosphere (soil/water surface), transpiration loss from plants
L	Surface water throughput (inflow from upstream)
M	Surface water throughput (outflow) and other losses (e.g. extraction for use outside the biosphere section)
N	Groundwater throughput (inflow)
O	Groundwater throughput (outflow) and other losses (e.g. extraction for use outside the biosphere section)
Y	Entry of contaminated water to near-surface aquifer
Z	Entry of contaminated water to surface water

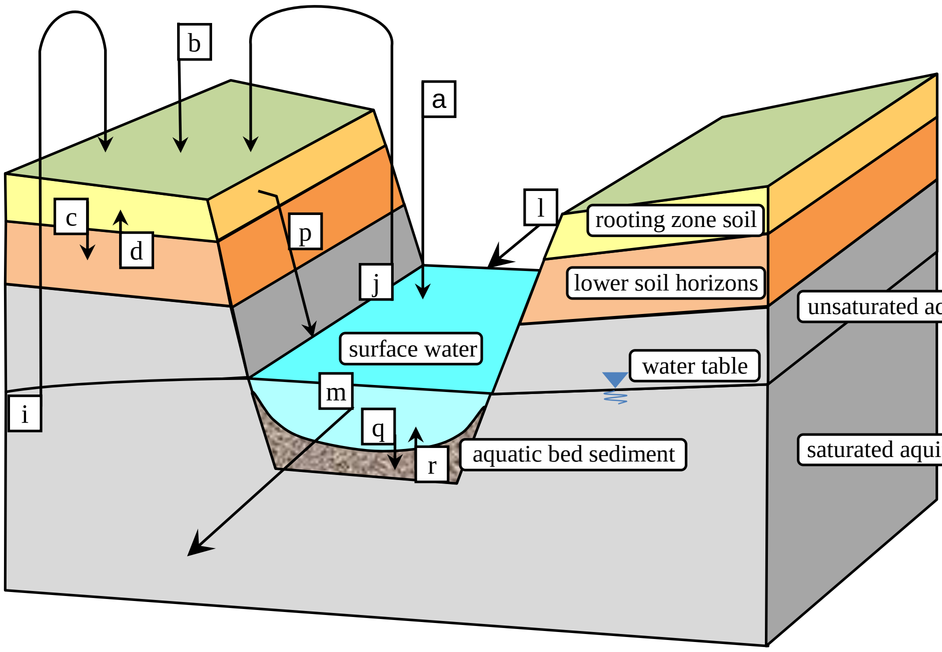


Figure A.32: Conceptualisation of the Principal Solid Material Fluxes in SwiBAC [Walke, 2012]

Nomenclature:

a External deposition on surface water (e.g. from erosion elsewhere)
b External deposition on soil surface (e.g. from erosion elsewhere)
c Bioturbation and water-mediated transport: rooting zone soil → lower soils
d Bioturbation: lower soils → rooting zone soil
i In irrigation water from the aquifer
j Flooding, dredging and irrigation: suspended solid material and bed sediment → soils (rooting zone)
l Suspended sediment throughput (inflow)
m Suspended sediment throughput (outflow)
p Erosion: rooting zone soil → surface water
q Deposition: waterborne solid material → bed sediment
r Resuspension: aquatic bed sediments → surface water

Contaminants are transported in the model by advection in the water phase, in association with mass movements of solids and by diffusion.

The model assumes that the rooting zone soil is well mixed on a timescale of one year and that the near-surface aquifer can be treated as a homogenous unit. Similarly, the intermediate soil horizons between the aquifer and the rooting zone are treated as a single entity. In the aquatic environment, a distinction is made between the surface water and bed sediments. These five compartments (rooting zone soil, near surface aquifer, lower soil horizons, surface water and bed sediment) are all that is required to model the transport of contaminants within the single biosphere section.

SwiBAC represents time-invariant biospere systems, but it can be parameterised to represent interglacial, periglacial, warm humid and warm arid climatic conditions.

A.8 GENERIC TYPES OF GEOSPHERE-BIOSPHERE INTERFACE AND THE EFFECTS OF ENVIRONMENTAL CHANGE

Based on the reviews reported in the previous subsections, it is clear that the greatest interest is in representing the GBI during unglaciated (boreal through to subtropical) conditions. This arises for several reasons including:

- The projected protracted duration of the current interglacial episode out to 50,000 years or more after present (Section A.1);
- Regulatory requirements in a semi-arid environment in which glacial episodes would primarily affect infiltration and irrigation requirements, but there would be no effects due to permafrost or the presence of ice sheets local to the site (Section A.2);
- A determination that the largest radiological impacts would occur during interglacial periods, albeit those occurring several hundred thousand years after present during future glacial-interglacial cycles (Sections A.3 and A.6);
- A regulatory requirement to address only the next few millennia in quantitative biosphere modelling (Section A.4);
- A site location beyond the boundaries of the ice sheets, though subject to frozen-ground effects and permafrost (Section A.5).

However, within the overall context of interglacial conditions, there are a wide variety of GBIs that require consideration. These broadly divide into two classes, i.e. those associated with wells and those associated with groundwater discharge. In the case of wells, there is little evidence that the time development of the environment needs to be taken into account, but for groundwater discharge the timescales of landscape development may be comparable with the timescales over which radionuclides move through the GBI and an explicit representation of that landscape development may be required. This leads to the need to develop rules for mapping radionuclides from one component of the environment to a different component as the landscape changes (see Sections A.3.3 and A.4.3).

In Section A.8.1, consideration is given to the various types of GBI that may be appropriate to wells and then, in Section A.8.2, consideration is given to the various types of GBI that may be appropriate to groundwater discharge zones. Discussion of the significance of environmental change is deferred to Section A.8.2, for the reason set out above. Finally, Section A.8.3 briefly discusses radionuclides that might be considered in the later, modelling stage of the project.

A.8.1 Generic Types of Geosphere-Biosphere Interface appropriate to Wells

The general approach has been to consider wells with relatively low abstraction rates, suitable for supplying water to a small number of people, but with enough capacity to encompass uses of water for domestic purposes, plant irrigation and the watering of animals. Thus, for example, RWMD (Section A.1.3) cites well abstraction rates of 1,560 to 7,300 $m^3\ a^{-1}$ (4.3 to 20.0 $m^3\ d^{-1}$). However, in semi-arid conditions, with extraction of water from a substantial depth, larger extraction rates have been proposed. For Yucca Mountain (Section A.2.3), the extraction rate prescribed by regulation is 3.7 10^6 $m^3\ a^{-1}$ (1 10^4 $m^3\ d^{-1}$).

Wells with low abstraction rates may be either dug wells down to depths of a few metres or boreholes drilled down to depths of a few tens of metres. However, boreholes constructed for industrial water use or commercial agricultural purposes may go down to greater depths (~ 200 m). For elicited distributions of depths of wells and abstraction rates, see Jackson *et al.* [2009].

Domestic wells may have sufficiently small abstraction rates to only constitute a minor perturbation to the flow in the aquifer from which the water is abstracted. However, wells with larger abstraction rates may give rise to significant drawdown in their vicinity (see Figure A.33).

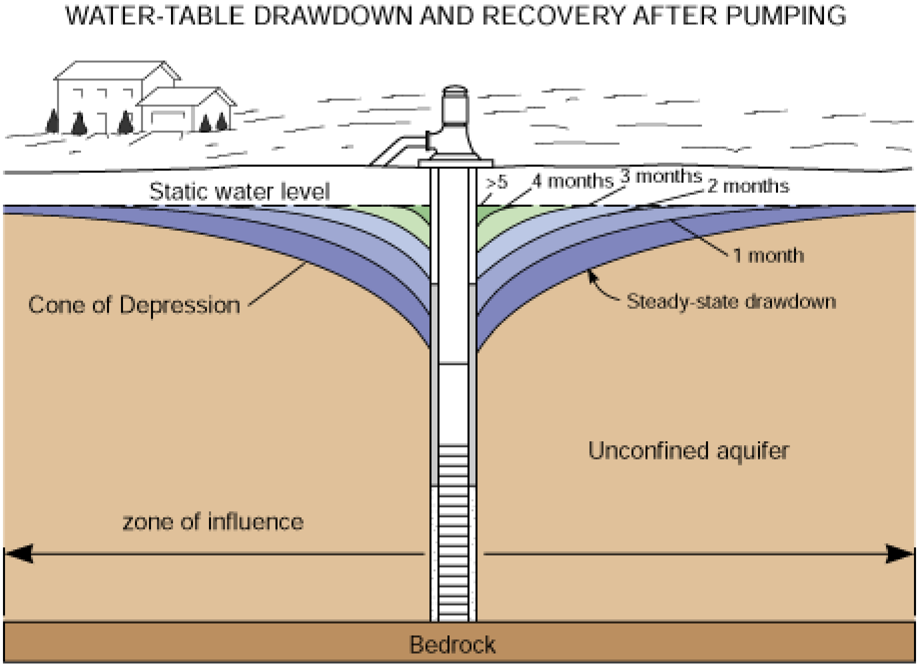


Figure A.33: Schematic Illustration of Well Drawdown (from www.kgs.ku.edu/HighPlains/atlas/apdrdwn.htm)

Figure A.33 emphasises that the degree of drawdown will depend on the recent pattern of pumping of the well. As pumping rates are likely to vary, the GBI around a well with a significant degree of drawdown is likely to be transient.

With deep wells and large abstraction rates, there will be a substantial inflow of water from the aquifer towards the well. Some of this water may be drawn up from deeper than the depth of termination of the well, so a contaminant plume may get drawn up from greater depth and captured by the well.

The illustration in Figure A.33 represents abstraction from an unconfined aquifer. Conditions near the surface are likely to be oxic, but conditions below the water table are likely to be reducing. With time-dependent pumping rates, there will be both fluctuating hydrological and fluctuating hydrochemical conditions in the vicinity of the well. Whereas shallow wells may primarily abstract recent meteoric waters, deeper wells may abstract a mixture of waters of different chemical composition and radionuclide content. The mix obtained will depend not only on the hydrochemical depth profile, but also on the depth intervals of the well that are screened.

Wells may also be introduced into confined aquifers. In this case, drawdown will not be an issue unless the abstraction rate is excessively large. However, flows will be focused on the well, as in the case of an unconfined aquifer.

In the above discussion, it is assumed that the types of well of relevance would abstract water from either an unconfined or a confined regional aquifer. In principle, wells can also abstract perched water. However, the amounts of water likely to be available will be limited and the sustainability of such wells will be doubtful. Furthermore, as the focus of interest is on contaminated groundwater upwelling from depth, the degree of contamination of perched water bodies is likely to be limited. Therefore, attention is here concentrated on wells that penetrate to below the depth of the local water table. However, unless cased through the overlying formations, they may also capture some perched water, which is likely to be of recent meteoric character.

A wide variety of rock types may host aquifers. In general, well construction would only be down to a depth sufficient to provide the requisite yield of abstracted water (recognising that the logistics of drilling might lead to a somewhat greater depth being drilled as a precautionary measure, if the drilling rig was available on site for longer than necessary to achieve the minimum acceptable depth of drilling).

From the assessment studies undertaken to date, the following aquifer host rocks are identified as requiring consideration:

- Sands, gravels and weathered breccias typically overlying a stratum of lower hydraulic conductivity;
- Weathered sandstone;
- Limestone;
- Volcanic alluvium and other types of alluvial deposits;
- Fractured hard rock (see, e.g. Figure A.11, where the aquifer is formed from a combination of sheet joints and gently dipping deformation zones).

More generally, the well may penetrate an aquifer where flow and transport can be described using a continuum approach or an aquifer where a discrete fracture network approach is more appropriate. In either case, consideration needs to be given to potential interactions between contaminant transport in the flowing porosity and diffusion into static pore water within the rock matrix. For fractured hard rock, consideration also needs to be given to the effects of fracture minerals on contaminant transport. Combining the above considerations, various generic types of well are proposed. These are set out in Table A.3.

Well Type	Well Depth (m)	Aquifer Type	Screened Interval	Abstraction Rate ($m^3\ d^{-1}$)	Water Use
Dug	1 to 10	Alluvium, sand, gravel	Most of well depth below about 1 m	< 5	Domestic, irrigation of a garden or smallholding
Shallow borehole	10 to 40	Weathered sandstone, limestone, deep alluvium	From a few metres or just below rockhead to the bottom of the borehole	4 to 20	Domestic, irrigation of a garden, smallholding or agricultural crops, animal drinking water
		Fractured hard rock		Strongly dependent on yield from fracture system, but probably from 4 to 20	
Deep borehole	40 to 200	Weathered sandstone, limestone, deep alluvium*	From just below rockhead to the bottom of the borehole	~ 1 10^4	Commercial agriculture or for industrial process water

Note: *Fractured hard rock is considered less likely, as the degree of fracturing and availability of groundwater is likely to decrease strongly with depth in areas likely to be selected for radioactive waste repositories.

Table A.3: Proposed Generic Types of Well[a]

The dug well would access a mix of recent meteoric water and upwelling groundwater. Conditions would be expected to be oxic and little drawdown of the water table would occur. The shallow borehole would also access a mixture of meteoric water and upwelling groundwater. Both oxic and reducing waters might be abstracted, but there might also be a perturbation to reducing conditions at depth, as a consequence of atmospheric oxygen entering down the borehole. The degree of drawdown would be moderate and variable, assuming that the aquifer was unconfined. However, it is possible that the aquifer might be confined, e.g. weathered sandstone beneath confining Quaternary deposits. The deep borehole might be into an unconfined aquifer, e.g. deep alluvium, or into a confined aquifer. In either case, a mixture of groundwaters of differing chemical composition and redox characteristics would be abstracted. For an unconfined aquifer, drawdown might be profound and time-dependent on seasonal

[a] Further examples of wells include managed aquifer recharge, whereby overexploitation is addressed through the injection of excess water as a means of replenishing groundwater. Geothermal storage systems and shale-gas fracking were also identified as examples of very deep wells that have not been considered to date in assessments, but that could involve disturbance at repository depth, potentially leading to new routes of release.

In some contexts, a multi-layered aquifer/aquiclude system may exist. Extraction of water from an upper aquifer, which may be uncontaminated, may draw water from a lower, contaminated aquifer. Alternatively, construction of a borehole may lead to stratified aquifers becoming interconnected.

and inter-annual scales (e.g. determined by irrigation demand), leading to changes in redox conditions at depth and the mix of waters entering the well.

A.8.2 Generic Types of Geosphere-Biosphere Interface appropriate to Upwelling Groundwater

In the case of upwelling groundwater, the areas of interest will generally be topographic lows in the landscape. However, such topographic lows may arise from various causes, e.g. they may be associated with structural characteristics such as deformation zones in hard rock or they may be incised valleys, as in the case at Bure (Section A.5.3). The near-surface flow pattern may differ depending on the type of discharge area. With an incised valley, the aquifer stratum will be intersected by the incision. This can lead to a spring or seepage line along the hillslope or a discharge to a stream channel and associated riparian areas at the base of the hillslope (see Figure A.34).

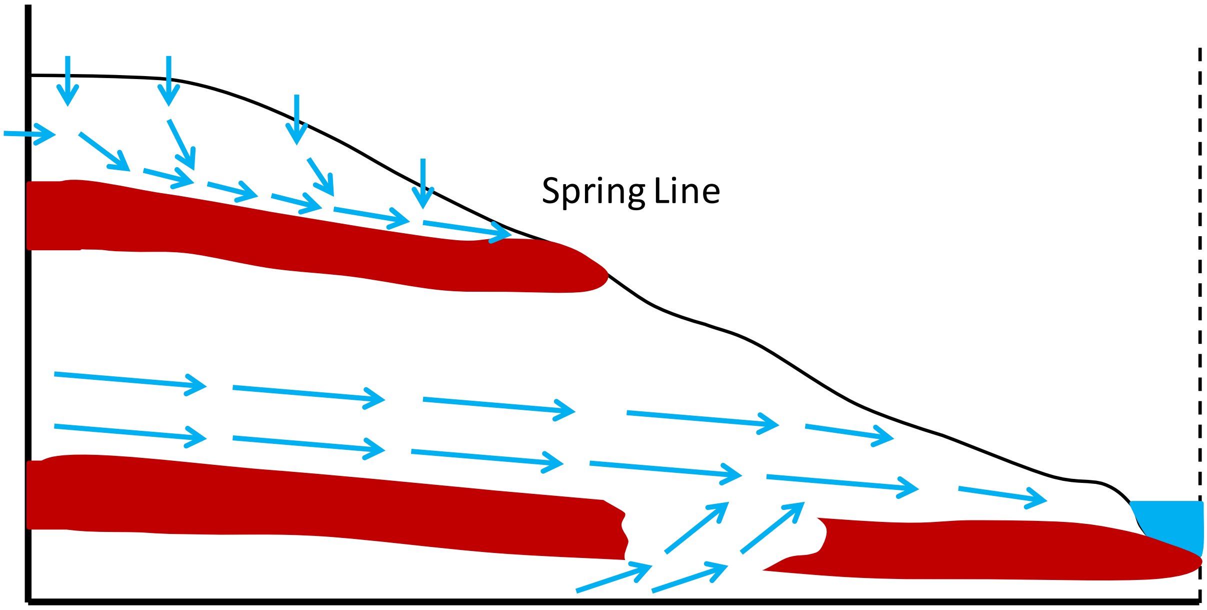


Figure A.34: Schematic of Discharges of Groundwater at a Hillslope. Brown represents strata of low hydraulic conductivity.

In Figure A.34, the upwelling contaminated groundwater mixes with more recent meteoric water that discharges to the stream banks and bed. However, in other contexts, the upwelling groundwater might mix with meteoric water discharging at a spring line.

With a structurally controlled low, the contamination may discharge into the bottom of the low, e.g. if it is a brittle deformation zone (see, e.g. Figure A.11). As discussed by both SKB and Posiva, this can be to the regolith underlying a variety of different types of biosphere objects, including marine bays, lakes, mires and agricultural land. Mixing of the contaminated water with recent meteoric water can occur in the regolith, in the overlying sediments or in surface water bodies. A schematic of how such discharges might occur in respect of a lake is provided in Figure A.35.

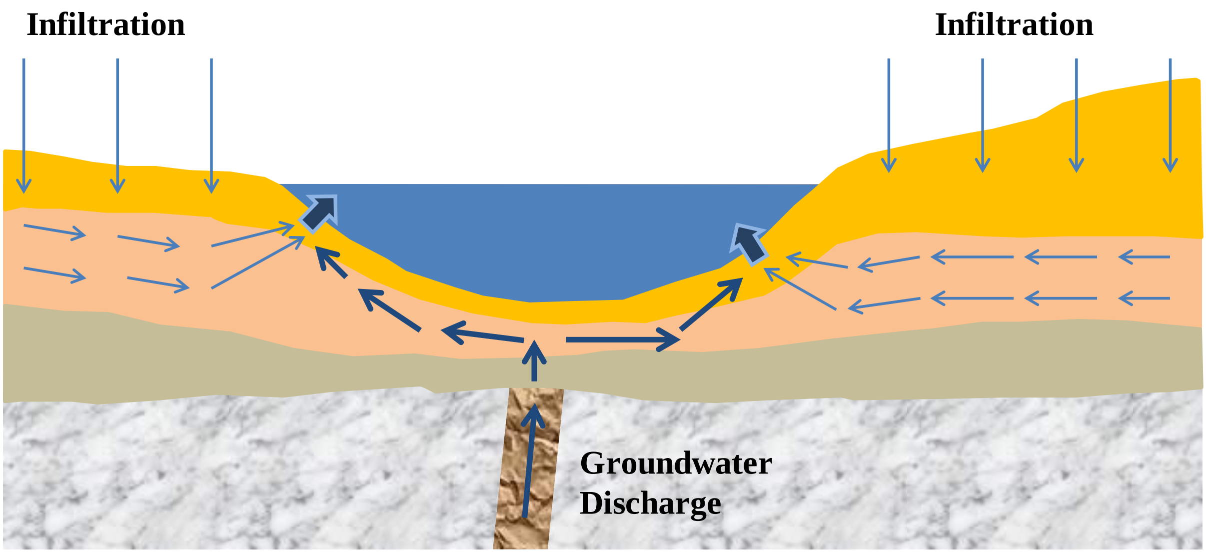


Figure A.35: Schematic of Groundwater Discharge beneath a Lake

The most appropriate interface to use will be governed by the following considerations..

a) There should be a flow path through the underlying geosphere that should either be through an aquifer that can be treated as a continuous porous medium or through a complex of interconnecting fractures that may, or may not, be lined with fracture minerals.

b) The geosphere flow path may discharge directly to soils, to a spring line or to a surface water body such as a river or lake. These cases are of rather limited interest, as the radionuclide flux from the geosphere discharges directly into a component of the biosphere that is represented in conventional models of the system. However, the case of discharge to soil may merit some attention, as there is the potential for important temporal changes in hydrogeochemical conditions in the zone where upwelling groundwater mixes with meteoric water. A simplified schematic of this is illustrated in Figure A.36.

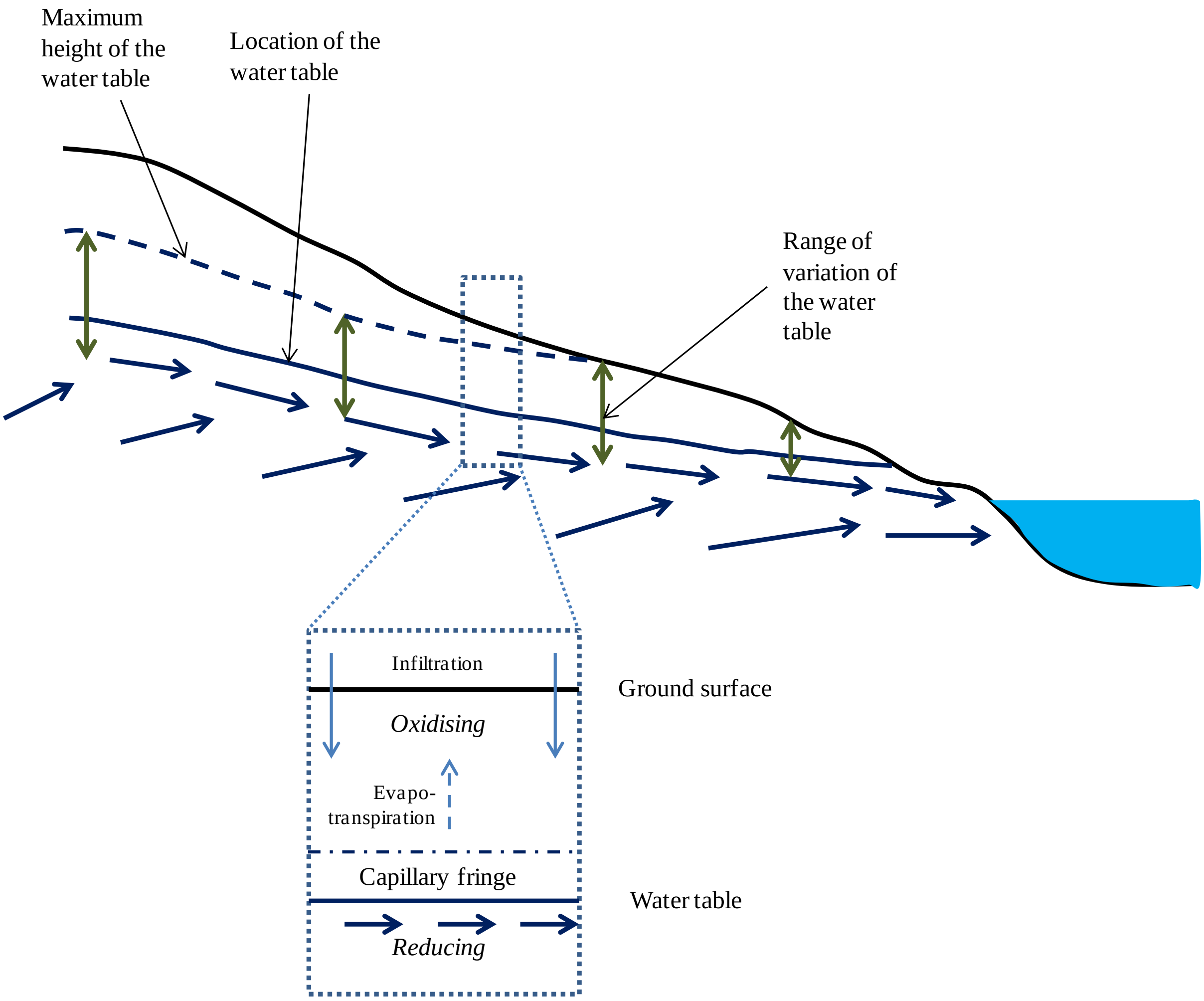


Figure A.36: Schematic of the Soil GBI for Upwelling Groundwater

Seasonally, and in response to individual precipitation events, the water table will vary over a significant range. This variation will, in itself, cause radionuclides to move up and down the soil column. At and below the water table, water and contaminant movement will be predominantly sub-horizontal and the water will emerge at the surface over a discharge area that shows seasonal and event-driven variations. There may also be sub-horizontal flows in the vadose zone above the water table, if there is significant anisotropy or textural variation in the soil, e.g. clay layers. However, in general, water movement in the vadose zone in most soils would be expected to be sub-vertical.

At any time and location on the hillslope, it is anticipated that there would be a transition from oxidising conditions above the water table to reducing conditions below it (inset to Figure A.36). This transition might occur mainly across the capillary fringe, where the soil is close to saturation. During precipitation events, infiltration will percolate downward through the soil column raising the height of the water table and between such events evapotranspiration will occur, distributed over the depth of the plant rooting zone. Not shown in Figure A.36 is surface runoff, which may occur either from the area where the water table intersects the ground surface or from upslope areas where the precipitation intensity exceeds the infiltration capacity of the soil. This runoff may be distributed as sheet flow or localised in gully flow.

As a result of changing hydrological and redox conditions, contaminant transport characteristics will vary with time. Thus, rates of sorption and desorption to soil solids will vary. However, the rapidity of variations in soil moisture and redox conditions may mean that an equilibrium representation of factors affecting contaminant transport cannot be adopted. Therefore, an explicitly kinetic approach may be required. Furthermore, there may be hysteresis between the wetting and drying phases of precipitation events or seasonal cycles that needs to be taken into account.

A further consideration in northern latitudes is that seasonal freezing of the soil zone may occur. Ground freezing decreases water movement, may expel solutes from the water as it freezes and can have mechanical effects on the soil structure. It may be desirable to include a consideration of these seasonal freezing effects in definition of a soil GBI.

c) The GBI may overlie an area of discharge from the geosphere to a regolith underlying a variety of superficial features. One example, with a fracture zone discharging to beneath a lake, is shown in Figure 3.3. However, it may be more useful to consider this interface in the generalised geometrical context shown in Figure A.37.

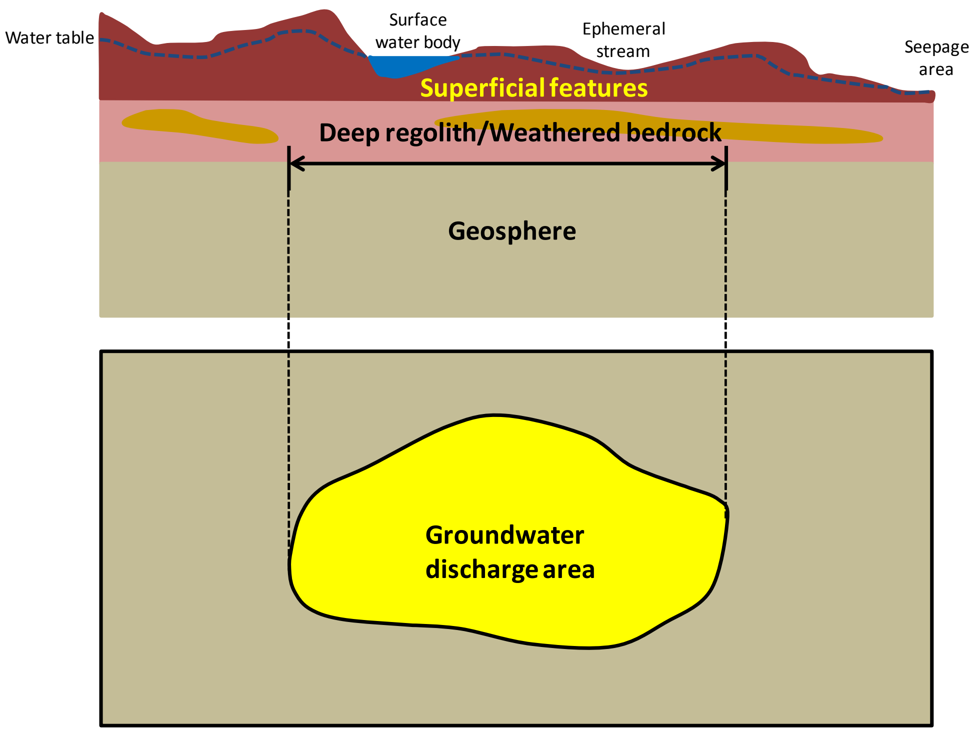


Figure A.37: Schematic of a Geosphere Groundwater Discharge Area and the Overlying GBI

The groundwater discharge area might comprise upwardly directed flow through a porous aquifer rock such as sandstone, limestone or chalk, or the intersection of a fracture zone in hard rock with the overlying weathered rock or regolith. The deep regolith or weathered bedrock may contain structural features and is shown as lying wholly beneath the water table, since location of the water table at substantial depth is not relevant to this GBI.

Water flows in the weathered rock or deep regolith will have an upward component inherited from the underlying groundwater discharge area. However, there will be interactions with the percolating meteoric water resulting in vertical hydrochemical gradients and the induction of a horizontal component of water flow that is responsive to the overlying topography. Thus, the groundwater discharge area and water composition at the interface between the deep regolith/weathered bedrock and the superficial features will differ from the composition and area at the interface between the geosphere and the weathered rock or deep regolith. Therefore, one component of a study of the GBI might investigate transport and dilution across this zone.

Groundwater and contaminants emerging from the weathered rock or deep regolith into the superficial features will tend to be subject to more localised flow regimes and discharge environments. Various cases are shown in Figure A.37, but these are not comprehensive. Thus, for example, discharges may occur to a surface water body and its immediate environs (e.g. a lake or river/stream), a stream channel where only ephemeral (seasonal) flows occur, or to a seepage area. The considerations illustrated explicitly in Figures A.35 and A.36 apply particularly in this zone.

Based on the discussion set out above, various types of GBI are suggested as deserving of consideration. These are set out in Table A.4.

Geosphere Type	Release via deep regolith or weathered rock	Nature of deep regolith or weathered rock	Type of release	Comment
Porous aquifer	No	Not applicable	Spring line	Not of interest. Water composition and radionuclide content similar to that in the deep groundwater, so no GBI issues of interest arise.
			Surface water body (stream, river, lake)	Of marginal interest. Water composition and radionuclide content determined by the mixing of aquifer water with stream, river or lake water. Can use a simple dilution calculation plus a mixing model for chemical speciation.
			Seepage zone	Of marginal interest, but rather more complex than the case of direct discharge to a surface water body. Water composition determined by interaction of aquifer water with meteoric water in the presence of soil solids in the seepage zone. Water would move downslope either as subsurface flow or surface runoff to reach the local drainage network. Further dilution and changes in composition would occur when it entered the surface water body. Limited range of land uses of the seepage zone.
			Soil	Of interest. Complex patterns of flow and transport in the soil zone, with seasonal and event-driven changes of relevance. Considerable modifications in water composition in moving from reducing to oxidising conditions. It is possible that kinetic effects could have significant influence on transport. Downslope movement of water and contaminants in the soil zone may require consideration, with progressive interactions with meteoric water during this transport.
Fault Zone	No	Not applicable	Spring line	Comments are similar to those for a porous aquifer. If a fault zone from hard rock outcrops at the surface, as is implied by the lack of deep regolith or weathered rock, there is unlikely to be a deep soil layer present. Therefore, the interface with soil is of less interest than if a porous aquifer is the source of contaminant discharge.
			Surface water body (stream, river, lake)	
			Seepage zone	
			Soil	
Porous aquifer	Yes	Porous medium	From aquifer across deep regolith or weathered rock into the superficial features	Of interest. It is assumed that transport is entirely in the saturated zone, so this reduces the complexity of approach required. However, there will be mixing of the deep groundwater with meteoric water in a zone of complex lithology and changing chemical composition of the groundwater. Temporal variations in conditions due to seasonal or event-driven effects will be limited and can probably be neglected.
		Fracture network		Not considered relevant. Unlikely to have fractured hard rock in the weathered zone overlying a sedimentary rock aquifer.

Table A.4: Categories of GBI for the Case of Upwelling Groundwater

Geosphere Type	Release via deep regolith or weathered rock	Nature of deep regolith or weathered rock	Type of release	Comment
Fault Zone	Yes	Porous medium	From aquifer across deep regolith or weathered rock into the superficial features	Considerations are very similar to those when the geosphere type is a porous aquifer. The main differences are likely to be in the spatial extent of the geosphere discharge and the chemical composition of the deep groundwater.
		Fracture network		Of interest. Transition from transport in a sparse network of fractures to transport in a much denser network potentially originating from a different cause (ice-sheet loading/unloading). Likely to have different types of fracture infill (e.g. calcite or clay minerals). Mixing with recent meteoric waters will occur and oxygen in meteoric waters may be depleted in the fractures over length scales of tens of metres, so the transition between oxidising and reducing conditions may be spatially extensive.
Either porous aquifer or fault zone	Yes	Porous Medium	From deep regolith or weathered rock through the superficial features to a spring line, surface water body, seepage zone or soil	Considerations are similar to those arising for direct release from a porous aquifer to these various surface environments. The main difference is that the water composition and contaminant concentrations will be modified by passage through the deep regolith or weathered rock.
Fault zone	Yes	Fracture network	From deep regolith or weathered rock through the superficial features to a spring line, surface water body, seepage zone or soil	Of interest. Complex flow paths are likely to exist in the fracture network and there may be a transition from larger-scale flow patterns to smaller-scale patterns as the influence of local topographic features will be greater closer to the surface. In addition to variations in fracture infills and oxygen consumption in the near-surface strata, there may be significant gradients in water composition due to microbial effects in superficial soils. Interactions with soils and other near-surface sediments (e.g. organic layers underlying surface water bodies) will need to be taken into account. The vadose zone may be of importance and seasonal and event-driven effects may propagate to significant depths down fracture zones of high hydraulic conductivity. This may be the most complex of the various GBIs listed as being of interest.

Table A.4: Categories of GBI for the Case of Upwelling Groundwater (Continued)

In general, the timescales of interest when simulating radionuclide transport across the types of GBI listed in Table A.4 will range up to a few thousand years, though longer timescales may be applicable for highly sorbed elements such as thorium and plutonium. Thus, in the first instance, it is suggested that modelling should relate to a single broad climatic condition, such as temperate, boreal or periglacial. However, this does not exclude investigation of the effects of climatic variations within one such state.

Climate varies on a variety of timescales varying from decades up to millennia (climate is typically defined over a 30 year interval, so inter-annual and seasonal variations are generally considered within the framework of a single longer-term climatic condition). Therefore, it may be of interest to investigate the extent to which a GBI would be perturbed by an extended period of variant climatic conditions, e.g. the Medieval Warm Period, the Little Ice Age, or the more extended Holocene Thermal Optimum at around 6,000 years Before Present.

As most work has been conducted on radionuclide transport under temperate conditions, it may be most appropriate to first address the modelling of the various GBIs under such conditions. This would mean excluding frozen ground effects. These could be studied at a later stage. If this were done, it is suggested that when the time came to address frozen-ground effects it might be appropriate first to consider the various GBIs under time-independent climatic conditions with seasonal ground freezing. Once this topic had been studied, it might be feasible to move on to consider how the GBI would evolve in transitions from temperate to boreal/periglacial conditions and from boreal/periglacial conditions to temperate conditions. Having studied transitions to seasonally frozen ground, it might be possible to extend the work to considerations of permafrost development. However, this is a more complex issue and impinges upon the approach to modelling the deep geosphere, as well as modelling of the GBI.

The discussion above does not address landscape evolution. Based on the various national programmes reviewed in earlier subsections, two cases are identified as being of interest. These are valley incision in a lowland landscape and post-glacial land rise subsequent to a glaciation. The latter is of particular interest in northern latitudes and has been studied extensively by SKB and Posiva. The main issues concern the inheritance of radionuclides as environmental media alter as a consequence of the sequence of transitions coastal bay → lake → mire → agricultural land, or variants on that sequence. Overall landscape models have been developed to represent such sequences and biosphere objects have been defined as components of those landscape models. Here, it is proposed that attention should be concentrated on the GBI characteristics of relevance to individual biosphere objects. The larger issue of integrating those biosphere objects into an overall, evolving landscape model is highly site specific. It has been undertaken for the Baltic Coastline, but not for other coastal areas, and it is not clear that further insights would be gained from including this type of landscape change within the current study.

Valley incision is of interest both in the UK and French programmes. In both cases, the main interest is in fluvial incision in a lowland regime. Geomorphological studies by Nirex of the deposits laid down by the Anglican glaciation (MIS 12) and the Late Devensian glaciation (MIS 2) indicate that fluvial incision has subsequently created valleys of depths of several tens of metres below the relatively smooth original palaeosurface [see Appendix 1 of Clayton, 1994]. As valley depths are similar in both cases, it seems that evolution towards an equilibrium valley profile is largely complete on a timescale of ten to twenty thousand years. It seems likely that significant future changes in valley profiles would occur only if there was a significant change in base level (normally sea level, but sometimes a hydraulic control upstream of the sea). If this were to occur, then the long profile of the stream or river would adjust through erosion and sedimentation such that it matched the new base level.

Overall, it seems unlikely that valley incision will significantly change the form of lowland landscapes over the remainder of the present long interglacial. In future interglacials, incision might occur into newly deposited glacial and post-glacial deposits. In such cases, the GBI might require representation of a time-dependent plume of radionuclides migrating through the new deposits in combination with the incision of a new valley into those deposits (Figure A.38).

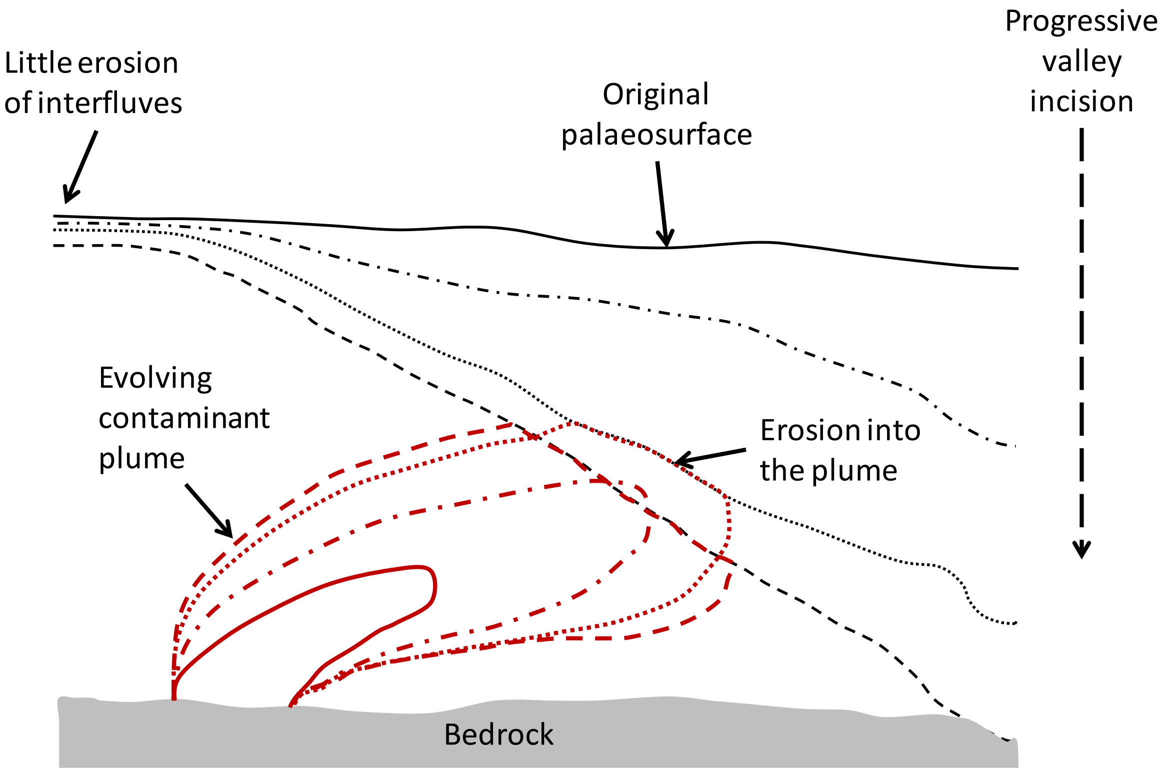


Figure A.38: Valley Incision interacting with a Developing Contaminant Plume

A.8.3 Radionuclides that might be considered

This appendix primarily addresses the types of GBI that have been considered in previous assessments with a view to defining the types of GBI that should be addressed in this study. To a large extent, this discussion is independent of the radionuclides to be represented in an assessment. However, later stages of the GBI characterisation involve an identification and description of the components of each GBI and of the processes influencing the properties of those components, with processes including those operating within one component and those relating different components. In identifying processes and evaluating their significance, account must be taken of the radionuclides of interest. For example, if the only radionuclides of interest have a single valence state and are not influenced by redox conditions, then processes that influence the spatial and temporal distribution of redox conditions in the GBI will be of little relevance.

From consideration of the various assessments that have been undertaken, a limited number of key radionuclides are identified below.

C-14: Often of significance in assessments. Carbon-14 has a relatively short half-life (5730 years), but can be of interest by both groundwater and gas-release pathways.

Ni-59: Sometimes of significance in assessments. Nickel is primarily selected as an illustrative transition metal that is also an essential trace element.

Cl-36: Simple anion, of considerable significance in many assessments. Chloride exhibits interactions with organic matter, is highly bioaccumulated by plants and may be susceptible to volatilisation.

Se-79: Of some significance in various assessments. Redox sensitive and exhibits several valence states in typical environmental conditions. Selenium is moderately highly bioaccumulated, biochemically active in its own right as well as being an analogue of sulphur and known to be susceptible to volatilisation.

Tc-99: Of some significance in various assessments. Technetium is highly mobile and bioaccumulated when present as pertechnetate. Conversely, reduced forms of the element can be strongly sorbed. Technetium has chemical analogies both with iodine and sulphur/selenium.

I-129: Of high significance in many assessments. Both iodide and iodate may be present in the environment. Iodine can be strongly accumulated in organic matter and participates in various biochemical processes. Iodine is susceptible to volatilisation.

Np-237: Often of significance in assessments. Neptunium is selected as an illustrative actinide exhibiting multiple valence states in environmental conditions.

The U-238 chain including Ra-226 and progeny: U-238 may be transported to the GBI, but radiological impacts are likely to be dominated by Ra-226 produced in the near-surface and transported through the GBI. The half lives of Ra-226 (1600 years), Pb-210 (22.2 years) and Po-210 (138 days) are all potentially comparable with transport times through different types of GBI. Furthermore, transport and loss of Rn-222 may be relevant in some contexts.

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ANNEX 1: CHARACTERISTICS OF THE ALLUVIAL AQUIFER AT AMARGOSA VALLEY, NEVADA

The following information is taken from Section 2.3.9.3.2.1 of US DOE [2009].

Laboratory and Field Testing: Laboratory-scale and field-scale tracer testing was conducted in the alluvium. To determine whether a single- or dual-porosity model best conceptualizes transport in the alluvium, three single-well injection-withdrawal tracer tests were conducted in borehole NC-EWDP-19D,and two single-well injection-withdrawal tracer tests, with two cross-hole tracer tests, were conducted at Nye County Site 22S. In each of the single well tracer tests, two non-sorbing solute tracers with different diffusion coefficients (a halide and a fluorinated benzoic acid) were dissolved in the same solution and simultaneously injected into the borehole, followed by a much larger volume of tracer-free groundwater (called chase water), and then pumped back after being allowed to remain in the aquifer for different time periods. Two cross-hole tracer tests were conducted at Nye County Site 22, from January to October 2005. The first test involved the injection of several tracers into the second interval from the surface in two different wells (22PA and 22PC), while the same interval was continuously pumped in 22S. The two injection wells were located in approximately orthogonal directions to each other relative to 22S (22PA is north, and 22PC is east), so flow and transport anisotropy could be evaluated. The second cross-hole tracer test was conducted in the same configuration as the first test, but only two tracers - iodide ion and perrhenate ion - and one injection interval (the second interval from the surface in 22PA) were used.

There was virtually no difference in the normalized responses of the halide and fluorinated benzoic acid in the tests at the Alluvial Testing Complex. The similarity of the responses for the tracers with different diffusion coefficients indicates that the diffusion between flowing and stagnant water was negligible over the time scales of the experiments. At well 22S, for the test with a 30-day rest period, the different responses of the two tracers suggested that diffusion may be occurring. However, there is also a significant difference between the responses of the same tracer (iodide) in the two tests with different rest periods. These differences cannot be accounted for by diffusion alone (particularly the shorter time to peak concentration in the longer-rest-period test), so tracer drift in the ambient flow field also influenced the single-well tracer responses at this location. The tracer responses for the cross-hole tests at well location 22S also showed a different response for the two tracers, suggesting some diffusion. Although there was no apparent diffusion between flowing and stagnant water in the single-well tracer tests at the Alluvial Testing Complex, the single-well and cross-hole tracer test results and interpretations at Site 22 collectively indicate dual-porosity transport behaviour in the alluvium at this location. However, the diffusion time and length scales are relatively short compared to those of the fractured volcanics, and an important conclusion is that, over the time and distance scales of importance for performance assessment calculations, the tracer test interpretations suggest that the alluvium will behave as a single-porosity transport system with an effective porosity equal to the sum of the flowing and stagnant porosities deduced from the tracer tests. The short diffusion time and distance scales are more consistent with a diffusion-into-grains (or blocks) conceptual model than a diffusion-into-layers conceptual model. However, longer diffusion time scales cannot be ruled out in the alluvium because of the short time and distance scales of the tracer tests relative to performance assessment time scales. As a result of these observations, diffusion was not considered for the alluvium in the site-scale saturated zone transport model, and the alluvium was represented using a porous continuum conceptual model.

Effective Flow Porosity: The advective velocity of groundwater is typically determined as the specific discharge divided by effective porosity. Effective porosity is that fraction of the porous medium through which groundwater flow occurs. The potential channelization of groundwater flow through higher permeability strata or facies within the alluvium may significantly reduce the effective porosity relative to the total porosity of the medium. Ranges of effective flow porosities for alluvial materials were presented in SNL [2008], and to supplement this information various methods were used to estimate effective flow porosity based on testing at the Alluvial Testing Complex and at Well 22S. A value of 10% was determined for effective porosity from borehole NC-EWDP-19D, based on the single-well tracer test results. Based on the cross-hole testing at Well Cluster 22S, the effective flow porosity values ranged from 3.6% to 18.7%. Total porosities ranging from about 20% to 30% were estimated for borehole NC-EWDP-19D, based on a borehole gravimeter survey. A total porosity estimate of about 40% was obtained using the storage coefficient from a cross-hole hydraulic test at the Alluvial Testing Complex, and the barometric efficiency of the formation. These total porosity estimates were considered when establishing upper bounds for the uncertainty distribution of effective flow porosities in the alluvium.

Alluvium Dispersivity: Longitudinal and transverse dispersion occurs due to heterogeneity in permeability within the alluvium. An estimate of longitudinal dispersivity in the alluvium (5 m) was obtained from the interpretation of the single-well tracer tests at NC-EWDP-19D that were used to calculate flow porosity. From the cross-hole tests at the Well 22S complex, longitudinal dispersivity values ranged from 1.6 to 10 m. Longitudinal dispersivity estimates were also obtained from several column tracer experiments conducted using groundwater and alluvium from borehole NC-EWDP-19D. Dispersivity values from these experiments ranged from 1.8 to 5.4 cm, which is consistent with the scale of the column experiments. Longitudinal dispersivity estimates from the single well tracer tests at the Alluvial Testing Complex are scale-dependent and thus exhibit a large uncertainty. The range of uncertainty in longitudinal dispersivity at any particular scale is between one and two orders of magnitude.

Radionuclide Sorption in the Alluvium: The migration behaviour of sorbing radionuclides in the saturated alluvium south of Yucca Mountain has been studied in a series of laboratory scale tests including batch sorption, batch desorption, and flow-through column experiments. The alluvium used in the experiments consists primarily of materials of volcanic origin similar to those found at Yucca Mountain (with some enrichment of clays and zeolites relative to common volcanic rocks, plus secondary mineral coatings on the detritus).

Experiments conducted using alluvial materials have focused on the transport characteristics of ^{129}I, ^{99}Tc, ^{237}Np, and ^{233}U. The first two radionuclides were determined to be non-sorbing, while the second two were moderately sorbed onto the alluvium. The goal of these experiments was to determine the sorption coefficients of the radionuclides onto alluvial materials under conditions similar to natural system transport. The alluvium samples used in the experiments were obtained at various depths from boreholes NC-EWDP-19IM1A, NC-EWDP-10SA, and NC-EWDP-22SA. Although the dominant minerals in the alluvium are quartz, k-feldspar, and plagioclase, considerable amounts of sorbing minerals like smectite (ranging from 3%to 8%) and clinoptilolite (ranging from 4%to 14%) were identified in the alluvium samples.

The results of all three experiments show that sorption of ^{233}U onto alluvium is fast and that, after one day of contact, the amount of ^{233}U adsorbed onto the alluvium changed little with time. The higher K_d value associated with alluvium material from well NC-EWDP-22SA may be due to the higher smectite and clinoptilolite content in the sample from this depth interval (522 to 525 ft below ground surface). The results obtained suggest that sorption coefficients in the alluvium range from about 3 to 13 mL/g for ^{237}Np and from about 3 to 9 mL/g for ^{233}U.

Batch sorption tests were also conducted to determine whether ^{233}U sorption behaviour differs in groundwater from different zones in the same borehole (e.g.,EWDP-19D, Zones 1 and 4). K_d values of ^{233}U measured in Zone 4 water were less than those measured in Zone 1 water. The major differences between these two waters were the lower concentration of divalent cations and the slightly higher pH in Zone 4 relative to Zone 1. These differences may result in greater complexation of ^{233}U to carbonate in Zone 4 water, as well as more sorption competition with divalent cations in Zone 4 water.

Laboratory column transport experiments were also conducted to determine sorption characteristics of radionuclides under flowing conditions in the alluvium. In column transport experiments using groundwater from boreholes NC-EWDP-19D (Zones 1 and 4) and NC-EWDP-10SA, ^{99}Tc and ^{129}I exhibited no retardation relative to tritiated water, which is consistent with the absence of sorption of these radionuclides in batch experiments. In some column experiments, particularly those involving ^{237}Np, a fraction of the radionuclide mass exited the columns at the same time as tritiated water. These observations are consistent with slow sorption kinetics of ^{237}Np as an explanation for the unretarded transport of a portion of the ^{237}Np (but see also below)

Breakthrough curves of ^{237}Np and tritiated water were studied as a function of flow rate in three columns packed with the same alluvium material. The results imply that the effective K_d values for a portion of the ^{237}Np mass in the higher flow rate experiments are significantly less than the K_d values obtained from batch sorption experiments using the same alluvium. However, the neptunium fractional mass recoveries were always significantly less than 1.0, indicating that a substantial portion of the neptunium sorbed strongly in the columns. These results differ from what was observed for plutonium in crushed tuff column experiments in that (1) neptunium is always retarded relative to tritiated water, regardless of the flow rate; (2) retardation increases with decreasing flow rate through the columns; and (3) neptunium continually elutes from the columns once it appears in the effluent. Whereas the plutonium responses were consistent with slow sorption kinetics with little desorption, the ^{237}Np behaviour is consistent with rapid sorption onto a distribution of sorption sites in the columns that have a wide distribution of effective K_d values. The flow-rate dependence of the neptunium breakthrough curves is consistent with a range of desorption rates for different types of sorption sites. As the flow rate decreases, a greater proportion of the neptunium mass in the columns becomes attached to sites with slow desorption rates. Similar long-tailed breakthrough curves with relatively low mass recoveries were obtained for ^{233}U in column transport experiments.

In summary, the column data indicate that, while a small fraction of radionuclide mass may arrive earlier than would be predicted using batch K_d values, this fraction decreases as flow rates decrease, and the K_d values obtained from batch sorption experiments reflect the behaviour of the majority of the radionuclide mass in the experiments. The data also indicate that the early arriving mass fraction may disappear altogether at low flow rates, such as those expected in the saturated zone. Cross-hole tracer tests at the 22S well complex also yielded sorption values for the tracer lithium that were compared with laboratory determined distribution coefficient values. The conclusion from this comparison is that the laboratory K_d values would probably result in underestimation of field-scale sorption/retardation in the alluvium if used in large-scale predictive transport models.

Transport of Radionuclides on Colloids: Radionuclides can undergo colloid-facilitated transport in both volcanic rocks and alluvium. Radionuclide-bearing colloids transported to the saturated zone may include (1) colloids, typically of clay or silica; (2) waste-form colloids resulting from degradation of spent nuclear fuel or glass; and (3) oxy-hydroxide colloids resulting from degradation of the waste package. These colloids are grouped into two types: those formed from hydrolysis of dissolved radionuclides (often called true colloids), and colloidal particles of other materials with attached radionuclides (called pseudo-colloids). The transport of true colloids is not included in the conceptual model of radionuclide transport in the saturated zone because these colloids would not be stable under prevailing geochemical conditions, or they would be strongly sorbed onto iron oxy-hydroxide colloids. The transport of pseudo-colloids in groundwater, and the mechanisms of sorption of radionuclides onto these colloid particles are included in the site-scale saturated zone transport model.

Colloid filtration rate constants and retardation factors were determined for alluvium in a number of laboratory and field experiments. These experiments were conducted using silica and natural colloids in addition to carboxylate-modified latex microspheres. Colloid attachment and detachment rate constants in the alluvium were derived through analysis of laboratory and field experiment data. Even though different sizes and types of colloids were used in the various tests, there was an apparent trend of decreasing attachment rate constant with residence time. In addition, field colloid transport data from the Netherlands (Schijven) were used to obtain field-scale estimates of colloid attachment and detachment rates to supplement site-specific, field scale data for the alluvium. The combination of the colloid selection, groundwater chemistry, and alluvium characteristics at the Schijven study site suggest that those field scale colloid filtration and detachment rate constants can be applied to Yucca Mountain alluvium. The colloid retardation factors were derived from colloid attachment and detachment rate constants evaluated from the results of the field and laboratory tests. Two field tracer experiments provide information regarding the migration of colloids in alluvium. A single-well test at the Alluvial Testing Complex and a cross-hole test at the 22S complex were conducted using microspheres as tracers. In both tests, detachment rate constants were estimated. For the cross-hole test, a filtration rate constant was determined as well.

APPENDIX B: METHODOLOGY FOR DEVELOPING CONCEPTUAL MODELS OF THE GEOSPHERE-BIOSPHERE INTERFACE AND ILLUSTRATIVE EXAMPLES

B.1 A METHODOLOGY FOR DESCRIBING THE GEOSPHERE-BIOSPHERE SUB-SYSTEM

The required methodology is considered to involve three stages:

- Stage 1: Identification and justification of the GBIs of interest;
- Stage 2: Description of those sub-systems;
- Stage 3: Development of conceptual models of those sub-systems to a sufficient level of detail that the descriptions provide a suitable basis for developing a mathematical model.

These stages can be broken down into more detailed steps, as illustrated in Figure B.1 and shown in more detail in Table B.3 in Section B.1.4. The justification for these steps and the activities associated with them are discussed in Subsections B.1.1 to B.1.3. A summary of the individual steps is provided in Section B.1.4, which also addresses the issue of how transitions between states of the GBI can be represented.

However, as in the case of the BIOMASS [2003] methodology for developing Reference Biospheres, these three stages are preceded by an initial stage in which the assessment context is defined. The selection of an assessment context relates to the performance assessment as a whole, so the assessment context components that need to be specified are located at a higher level than the GBI methodology discussed herein and are as set out in Section B2 of BIOMASS [2003]. These components are:

- Purpose of the assessment (from testing of initial ideas for a disposal concept to support for a disposal license application requiring a detailed, site-specific performance assessment against regulatory criteria);

- Endpoints of the assessment (e.g. effective dose to a representative person, radionuclide fluxes to the biosphere, absorbed dose rates to biota);

- Assessment philosophy (e.g. degree of pessimism to be adopted, extent to which stylized situations can be used as a basis for compliance demonstration);

- Repository system (including basic assumptions for waste characteristics, packaging, engineered system, and location within the host rock);

- Site context (including basic assumptions for geographical, climatic, geological and geomorphological aspects);

- Source term (in the present context, potential radionuclide fluxes entering the GBI, including consideration of their spatial and temporal distribution);

- Time frames for assessment (noting that both the source term and the endpoints of the assessment may differ among time frames);

- Societal assumptions (e.g. level of technological development, rural or urban, patterns of behaviour).

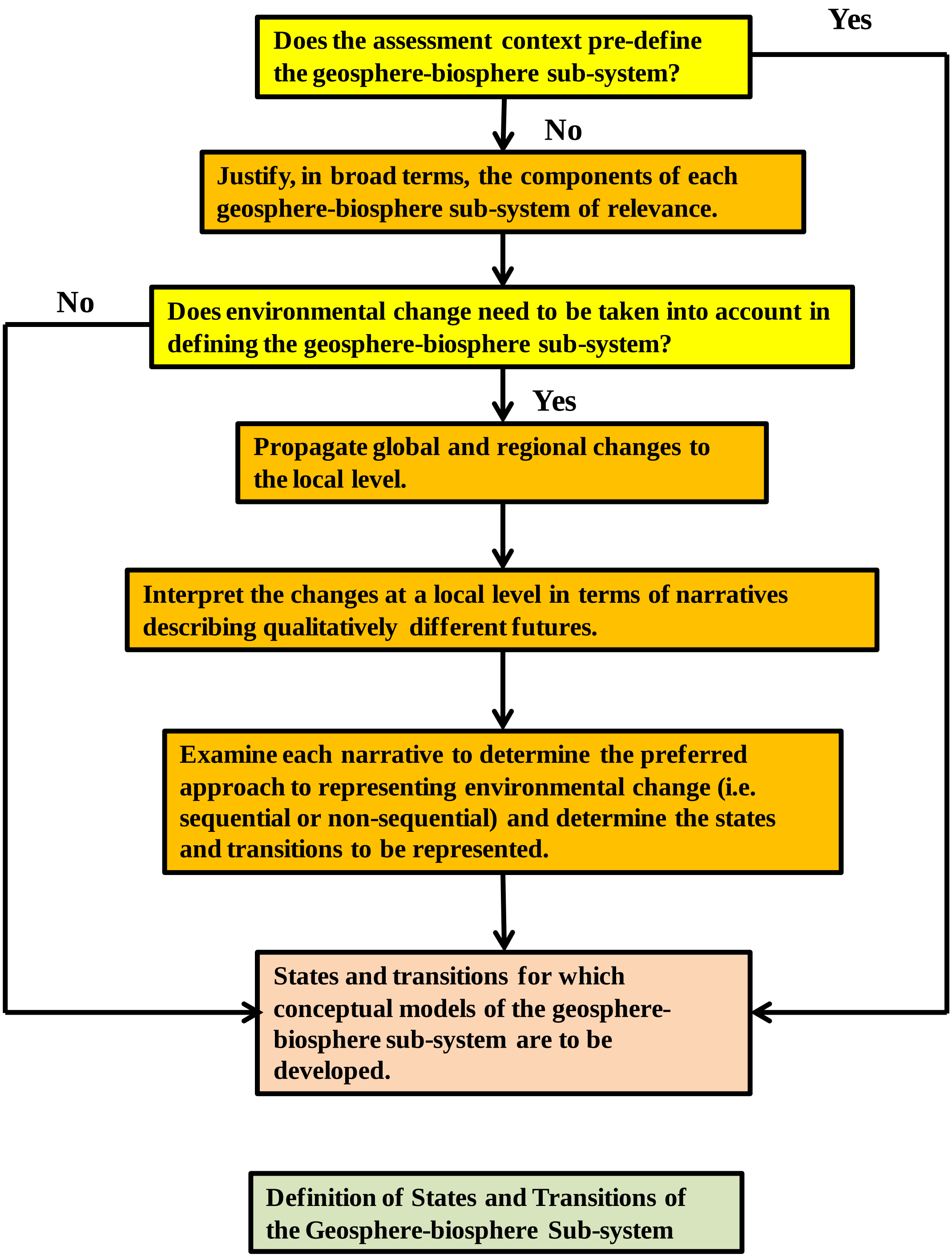


Figure B.1a: Initial Steps in the Methodology leading to the Definition of States and Transitions of the Geosphere-Biosphere Sub-system (GBI)

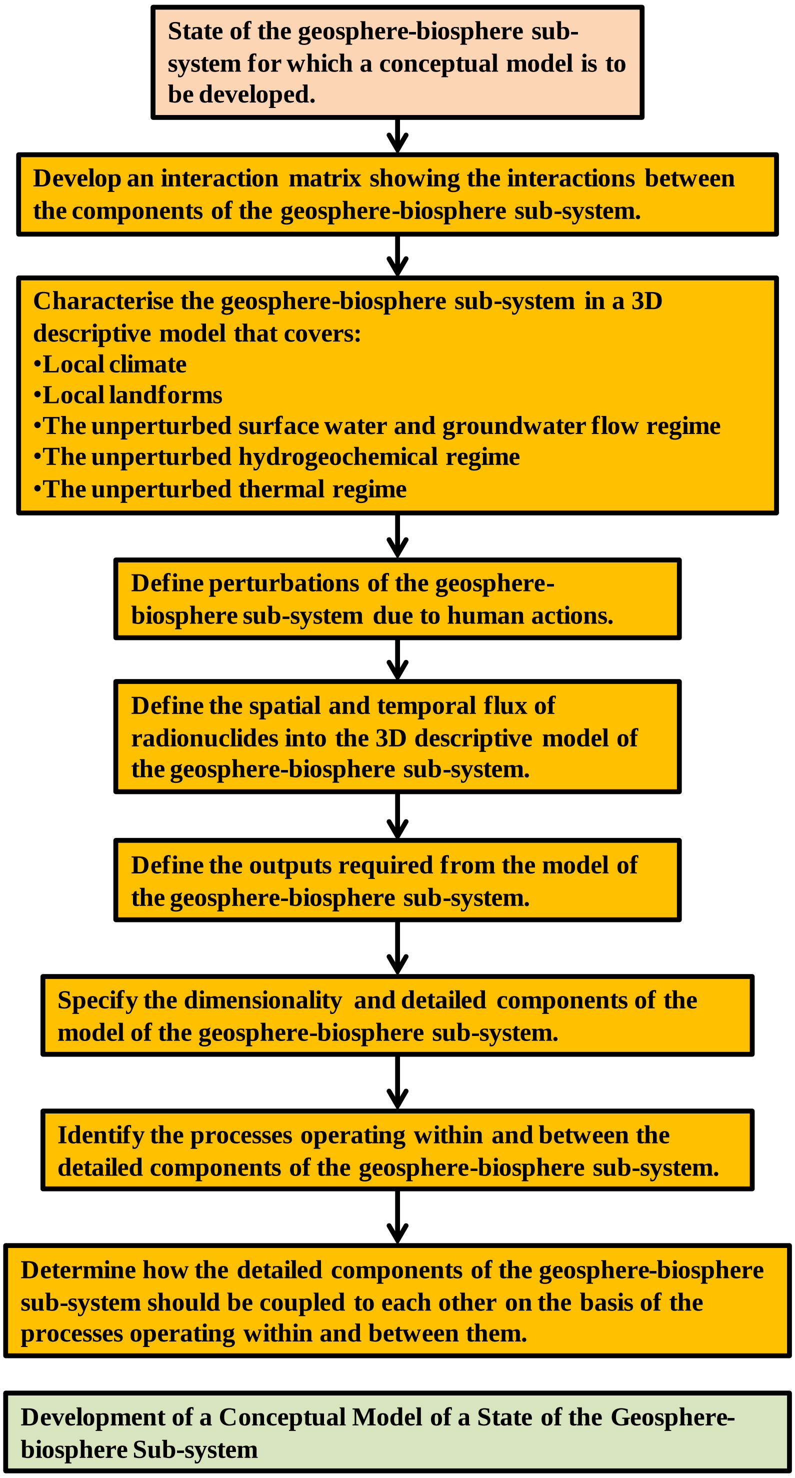


Figure B.1b: Further Steps in the Methodology leading to the Development of a Conceptual Model of a State of the Geosphere-Biosphere Sub-system (GBI)

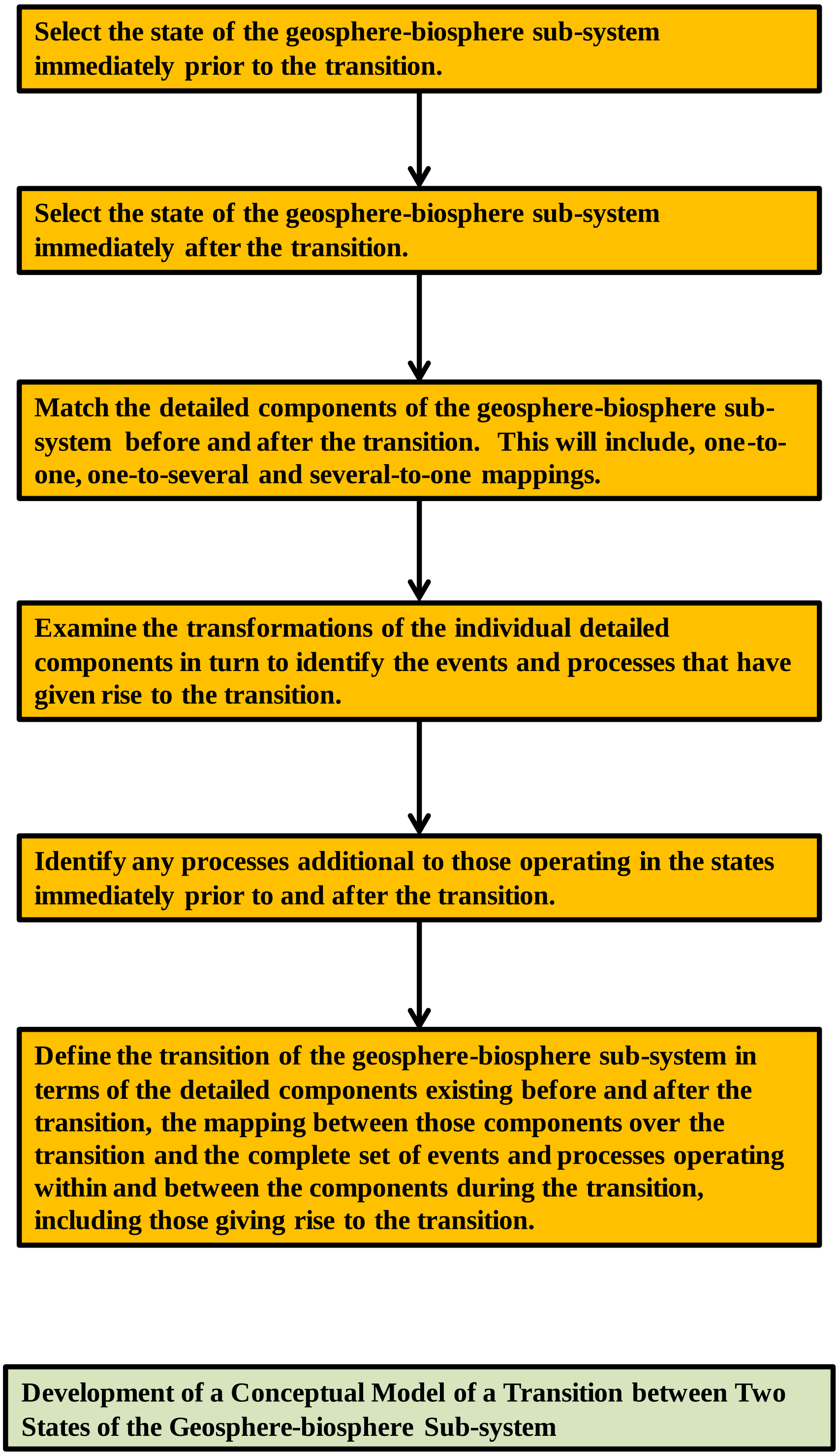


Figure B.1c: Additional Steps in the Methodology for handling Transitions between States

B.1.1 Stage 1: Identification and Justification of Geosphere-biosphere Sub-systems

As with the BIOMASS [2003] methodology applicable to the biosphere, the overall approach consists of up to three steps.

Step 1: Identification and Justification of Components of the Geosphere-biosphere Sub-system

In Step 1, the assessment context is reviewed to establish whether or not it pre-defines the GBI. If it does not, the components of the GBI or sub-systems to be represented are identified and justified according to an interpretation of the assessment requirements. In practice, whereas the biosphere is sometimes prescriptively defined in regulation, this would not generally be the case for any aspects of the deeper system, so it will normally be necessary to identify and justify the components of each GBI.

To a large extent, these components are similar to those for the biosphere. They comprise:

- Climate and atmosphere (as these are relevant to determining the upper boundary conditions that are imposed on the GBI);
- Geographical extent (which determines the lateral spatial extent of the GBI);
- Location (which determines factors such as distance from the present-day coastline);
- Topography (determines the geometry of the GBI and is a strong control on the boundary conditions that apply to it);
- Human community (of relevance because human activities, such as the use of wells, and land uses can affect the characteristics of the GBI);
- Near-surface lithostratigraphy (includes the composition and structure of soils, sediments and bedrock down to the base of the GBI; the base of this sub-system will depend on the assessment context, but will generally be such as to include the whole depth of weathered bedrock and any fracture systems that originated or were substantially modified during the Quaternary, since these factors are evidence of the pervasive influence of surface processes on this zone);
- Water bodies (including both surface and sub-surface water bodies down to the base of the GBI);
- Biota (terrestrial and aquatic organisms that are either present within the GBI or are present in the overlying biosphere and have an influence on the GBI).

In contrast to the biosphere, there is also a need to address the issue of where the upper boundary of the GBI is set. This might be at the upper boundary of soils and sediments where they interface with either the atmosphere or surface-water bodies. However, alternatively, it could be at the base of any soils and sediments present, such that it immediately overlies deeper unconsolidated material or weathered bedrock.

It is of interest to note that this step precedes the consideration of environmental change (this occurs in Step 2, which is discussed below). Thus, the components of the GBI set out above can only be defined in broad terms, since they will be subject to modification as the climate and landscape alter. In many cases, this will pose fewer difficulties than with the biosphere, since the GBI is expected to be less affected by environmental change than the biosphere. However, in assessment contexts in which it is necessary to take account of environmental change and in which that environmental change has profound effects on the GBI, it will only be possible in Step 1 to define the GBI at the present day, deferring definition of the GBI in the future to Step 2.

Step 2: Consideration of Environmental Change

In Step 2, consideration is given to whether environmental change needs to be taken into account in defining the GBI(s) to be taken into account. If there is no explicit guidance from the assessment context, or if the assessment context expressly requires environmental change to be considered, the following questions need to be addressed:

- what are the relevant mechanisms causing environmental change?
- what are the potential impacts of the resultant environmental change on the GBI?

As to the relevant mechanisms causing environmental change, these are the External Features, Events and Processes (EFEPs) identified in Figure B3 of BIOMASS (2003) and illustrated in Figure B.2.

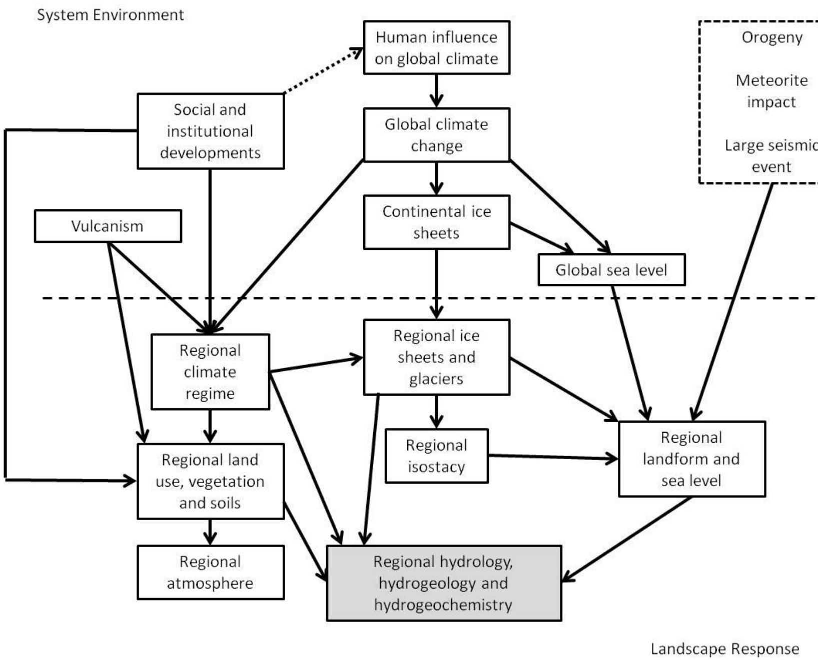


Figure B.2: Mechanisms causing Environmental Change

(Based on BIOMASS [2003], Figure B3, but with 'Regional hydrology' replaced by 'Regional hydrology, hydrogeology and hydrogeochemistry', which is shown shaded)

Identification of the potential impacts of these environmental changes on the GBI requires propagation of regional changes to the local level. This can be done by combining the regional landscape responses shown in Figure B.2 with the GBI components given previously. An illustration of this is shown in Table B.1, where some examples of regional to local influences are listed. Note that the regional factors are those listed below the dashed line in Figure B.2 and the aspects of the local environment are those set out in Step 1. Also, note that these examples are not intended to be comprehensive. In practice, such influences would be determined comprehensively within a specific assessment context, which would include a description of the various components of the system at both regional and local levels. Thus, the generic descriptions of potential influences in Table B.1 would be replaced by more specific descriptions appropriate to the assessment context.

Table B.1: Regional Influences on Components of the Local Environment

Regional Factor	Aspect of the Local Environment	Illustrative Influences
Climate	Climate	Climate requires downscaling from the regional to the local scale.
	Atmosphere	Determines aspects such as relative humidity and local wind velocities that may be used in assessment modelling.
	Topography	Influences the erosional-depositional regime, but this is mainly an indirect effect through influences on local climate and water bodies.
	Near-surface lithostratigraphy	As for topography, but there are also influences on soil formation and alteration that are largely an indirect effect via local climate. Similarly, ground freezing effects, e.g. pingos and patterned ground, can arise indirectly through changes to the local climate.
	Water bodies	Direct effect, e.g. on changing lake levels, where these are determined by regional-scale moisture balances.
	Biota	Direct effect on species ranges. Indirect effect via local climate on local habitats, communities and ecosystems.
Ice-sheets and glaciers	Climate	Local climates are strongly modified close to the margins of ice sheets and glaciers.
	Atmosphere	The air flow regime over ice sheets and glaciers influences air temperature, humidity and aerosol characteristics. To a large extent, these effects are reflected in changes to local climates downstream of ice sheets and glaciers.
	Topography	Ice sheets and glaciers have a strong influence on the local erosional and depositional regime. This includes sub-glacial erosion, moraine and esker formation, and a variety of effects in the vigorous fluvial regime that typically exists at and beyond the margins of the ice.
	Near-surface lithostratigraphy	As for topography, but there are also effects of loading and unloading of the superficial strata (e.g. Induction of sheet joints in hard rock and production of low-angle thrust faults in unconsolidated deposits).
	Water bodies	Includes the formation of ice-marginal lakes. There are indirect effects that arise from isostacy, since depression beneath an ice sheet can result in flooding of the area when the ice sheet retreats.
	Biota	Limited habitats available either on the ice or in ice-marginal areas due to the instability and lack of soil development in such areas.

Table B.1: Regional Influences on Components of the Local Environment (Continued)

Regional Factor	**Aspect of the Local Environment**	**Illustrative Influences**
Isostacy	Climate	Changes in altitude will have an effect on climate, but this is likely to be a minor consideration compared with the ranges of climatic conditions that will need to be considered.
	Atmosphere	No significant effects.
	Topography	In general, isostatic effects result in an overall upward or downward movement at a local scale. However, a degree of tilting may occur. Also, in ice-marginal locations, there may be a transition from downwarping beneath the ice to upwarping beyond its margins (the forebulge effect).
	Near-surface lithostratigraphy	Mainly indirect effects through changes to topography and water bodies that affect the erosional and depositional regime.
	Water bodies	Depression or uplift can affect the potential locations of water bodies. Includes shoreline regression and transgression, and changes to lake thresholds. Sub-surface water bodies may also be affected by differential changes in altitude of the strata, e.g. of a regional aquifer.
	Biota	Limited direct effects, but there may be major indirect effects, e.g. through influences on the location and characteristics of water bodies.
Landform and sea level	Climate	The regional topography will have an influence on local climate. Changes in sea level at a regional scale may result in emergence or flooding of large areas (e.g. the Southern North Sea) and this would have some effects on local climate.
	Atmosphere	There may be effects on atmospheric aerosol concentrations depending on the distance of the sea from the local area of interest.
	Topography	Regional landform and sea level are a strong influence on the local erosional and depositional regime, e.g. by defining base level and the long profiles of rivers.
	Near-surface lithostratigraphy	As for topography.
	Water bodies	There are direct influences on the flow regime both for surface and sub-surface water bodies. These are due both to changes in physical gradients and alterations in the location of the saline interface.
	Biota	Direct effects will arise from changes in altitude and aspect, but more substantial indirect effects are likely to arise from changes to the location, flow and composition of water bodies.

Table B.1: Regional Influences on Components of the Local Environment (Continued)

Regional Factor	Aspect of the Local Environment	Illustrative Influences
Hydrology, hydrogeology and hydro-geochemistry	Climate	Limited effects due to local changes to the hydrological cycle, but such changes are likely to be minor compared with changes in local temperatures and precipitation due to regional changes in climate.
	Atmosphere	Minor effects due to changes in the hydrological cycle.
	Topography	Hydrological flows are a determinant of the erosional and depositional regime.
	Near-surface lithostratigraphy	As for topography.
	Water bodies	The characteristics of both surface and sub-surface water bodies are determined, in part, by flow characteristics and chemical compositions of waters established at a regional scale, e.g. the influence of a major river flowing through the local area or of a regional aquifer underlying the local area.
	Biota	Water flows and water chemistry are strong determinants of viable habitat types and ecosystems.
Land use, vegetation and soils	Climate	Limited effects, e.g. through controls on evapotranspiration.
	Atmosphere	Limited effects due to releases of gases from the soil-plant system (carbon dioxide and methane) and the production of aerosols.
	Topography	May influence the erosional and depositional regime, e.g. as a consequence of desertification at a regional scale.
	Near-surface lithostratigraphy	Indirectly through changes to the erosional and depositional regime, and through effects on local biota.
	Water bodies	Potentially significant control on local water availability as a consequence of the effects of evapotranspiration. May affect the composition of local waters as a consequence of particular land uses, e.g. due to fertiliser amendment of soils.
	Biota	Sets a regional context for local habitats, communities and ecosystems.

Having identified the EFEPs of relevance in a specific assessment context and propagated their influence from a regional to a local level, there remains a requirement to interpret the combined influence of these EFEPs on the disposal system in terms of qualitatively different futures (corresponding to Step 2.3 of the BIOMASS [2003] approach to defining Reference Biospheres). This interpretation may make use of tools such as interaction matrices to define how the various components of the local system interact under the influence of EFEPs propagated down to the regional level and may also make use of transition diagrams, as developed in BIOCLIM [2004], to represent the time-evolution of the components of the GBI in relation to each other. However, the overall aim is to provide narratives describing the various qualitatively different futures, as these narratives provide the key input to Step 3 of the identification and justification process.

Step 3: Examination of Narratives of Environmental Change

In Step 3, each narrative is examined to determine the preferred approach to representing environmental changes that affect the GBI in an assessment. In making such a decision, account has to be taken of the narrative itself, the overall assessment context, and decisions that are being made as to how other parts of the disposal system are to be represented, e.g. if the biosphere is assumed to be time-independent over a particular interval, it may difficult to match it to a time-dependent GBI, so it may be preferable to adapt the approach such that both the biosphere and GBIs are either time-independent or time-dependent.

As with the biosphere [BIOMASS, 2003], the main choice in modelling approaches is between a non-sequential and a sequential approach. In the non-sequential approach, the judgment is made that, taking account of the narrative description of projected environmental changes at the regional and local scales, it is possible to identify a finite number of discrete, quasi-equilibrium states of the GBI that are adequately representative of key stages in the narrative. It is further judged that time-invariant models for each of these states can then be developed and applied independent from one another, with their projected sequence disregarded. This approach requires that radionuclide distributions in the GBI and fluxes from that system to the biosphere during any particular state are not strongly influenced by radionuclide fluxes that entered the GBI prior to the occurrence of that particular state.

In the sequential approach, the separation into non-interacting states is judged invalid, unnecessary or otherwise inappropriate. Thus, the GBI is represented either through simulating a sequence of discrete states or via quasi-continuous variations of the properties and characteristics of GBI components [see BIOMASS, 2003]. An intermediate position is advocated in BIOCLIM [2004], according to which the analysis relates to a sequence of states and also addresses the effects of the periods of transition between these states. In this approach, the characteristics of the time-independent states are first defined on a component-by-component basis. Following this, transitions between any pair of states are characterised by describing how the characteristics of the components alter over the transition from those of the pre-transition state to those of the post-transition state (see further Section B.1.4).

As noted in BIOMASS [2003], it is not easy to draw an absolute distinction between ‘continuous’ and ‘discrete’ (step-wise incremental) representations of sequential change. Step-wise incremental approaches become continuous in the limit of infinitesimal time steps. The key issue is to ensure that the discontinuities in system characteristics implicit in a step-wise approach do not introduce unacceptable artefacts into the results of the assessment.

Although a non-sequential approach can often be justified for the biosphere (due both to the short residence times of key radionuclides and the need to make broadly based judgments as to its characteristics), such an approach is more difficult to justify for the GBI. Radionuclide residence times in this zone are likely to be more protracted than in the biosphere and its time development is likely to be more constrained by its physical and chemical characteristics than that of the biosphere. Indeed, the underlying narrative of environmental change will imply a corresponding narrative as to how the GBI alters with time. Thus, it seems likely that a sequential approach to geosphere-biosphere representation will be preferred. However, this leaves open the issue as to whether that representation should be continuous or discrete. In a continuous approach, radionuclide transport would be modelled through a continuously changing environment. In practice, this would imply the setting up of a set of linked differential equations representing both environmental change and radionuclide transport. In the discrete approach, radionuclide transport could be modelled as occurring within a fixed environment during each state of the GBI. However, rules would need to be provided to map the radionuclide distribution present at the end of one state to the radionuclide distribution at the beginning of the next state. Those rules would reflect two considerations:

- the processes involved in causing the GBI to move from one state to another (e.g. transformation of a lake to a mire by terrestrialisation);

- the model structures adopted for the two states (e.g. requiring radionuclides present in the soil/sediment column to be reassigned from the layers defined before the transition to the layers defined after the transition).

Thus, mapping rules depend on both the changing characteristics of the sub-system and the way in which those changing characteristics are represented in the adopted model of the sub-system (see also Section B.1.4).

In the examples developed in this report, narratives of environmental change have been interpreted in terms of a sequence of GBI states. This has been done to facilitate the next stage of the analysis, which is to develop conceptual models for the GBI. This is most easily done by developing conceptual models for each of a set of environmental states. However, this does not preclude combining these conceptual models to generate a conceptual model of a GBI developing from one state to another. Nor does it preclude using the conceptual model for a particular state in stand-alone mode in a non-sequential approach.

B.1.2 Stage 2: Description of Geosphere-biosphere Interface

Outputs from Stage 1 of the methodology set out in Section B.1.1 are narratives of environmental change and a determination as to whether each of those narratives should be interpreted in terms of a continuously changing GBI, a sequence of periods with a GBI defined for each, or just a single time-independent GBI. Here, it is assumed that each narrative is decomposed into a sequence of periods on the principle that, if the GBI is described for each such period, then a continuous account can be created by taking these descriptions and combining them to generate descriptions of the transitions between periods, both in terms of transitional characteristics and the events and processes that give rise to the transition (Section B.1.4).

Thus, the GBI descriptions developed below are essentially ‘snapshots’ from a particular narrative at a particular time. However, they do include an account of the events and processes that are operating to modify the sub-system at that time.

At the beginning of this stage, the components of the GBI are already defined (climate, atmosphere, topography, near-surface lithostratigraphy, water bodies, biota). For a particular stage in a narrative, these components need to be characterised in specific terms and their inter-relationships need to be identified. This can be done through the use of an interaction matrix (Step 4 of the methodology). Figure B.3 illustrates the general form of such a matrix and Figure B.4 illustrates how such a matrix might be completed for a particular GBI (an inland, surface-water catchment developed in Quaternary sediments overlying a chalk aquifer in Lowland Britain).

Climate		*Erosion and Sedimentation*			
	Atmosphere				
		Topography			
			Near-surface Lithostratigraphy		
				Water Bodies	
					Biota

Figure B.3: General form of an Interaction Matrix for the Geosphere-biosphere Sub-system

In Figure B.3, the local climate is shown influencing the local topography through the processes of erosion and sedimentation. Relevant interactions are shown in the off-diagonal elements and the interaction matrix is read in a clockwise direction, as indicated in Figure B.3.

Figure B.4, is an illustration that is relevant to a relatively detailed generic assessment applicable to Lowland Britain under present-day climatic conditions. It relates to a surface-water catchment with a river channel incised into a thick layer of superficial Quaternary sediments laid down during the Anglian glaciation of MIS 12 (approximately 400 ka BP). Large parts of East Anglia conform to this situation. Note that, in Figure B.4, both near-surface lithostratigraphy and water bodies have been distinguished into various components.

Köppen-Trewartha climate state DO (temperate oceanic)	Determines seasonal temperatures and precipitation. Relative humidity generally relatively high. Most precipitation falls as rain rather than snow.	Precipitation-induced incision, but at a very low rate, as river profiles are close to equilibrium. Negligible rates of incision on interfluves.	No significant influence on structures, as ground freezing is of negligible importance.	No significant influence.	Seasonal temperatures and precipitation define flow rates in all components of the surface-water system. The baseflow in the main river channel is determined by longer-term variations in climate, being governed by discharge from the chalk aquifer.	Seasonal temperatures and precipitation govern the water content of soils and perched aquifers. Relatively wet summers mean that only limited drying of soils occurs in the summer months.	Seasonal temperatures and precipitation govern the recharge of the chalk aquifer from areas close to local interfluves, but the main recharge of this aquifer occurs at a broader regional scale.	Seasonal temperatures and precipitation determine a moderate irrigation requirement in some, but not all, years.
No significant influence.	**Low to moderate levels of atmospheric pollution. Generally low dust loads. Limited influence of marine aerosols (inland site assumed).**	No significant influence.	No significant influence.	No significant influence.	No significant influence	Influence on hydrochemistry negligible compared with the effects of agricultural practice.	Influence on hydrochemistry negligible compared with the effects of agricultural practice.	No significant influence.
Minor differences in climate between the river valleys and the more exposed plateau into which they are incised.	Minor differences in pollution and dust loads between the valleys and the plateau.	**Subdued topography. V-shaped river valleys incised to a depth of a few tens of metres and sometimes penetrating through the Quaternary sediments to the underlying Chalk.**	Incision penetrates through the layered Quaternary sequence and into the underlying chalk. Little further erosion is occurring, so the exposed strata and the hydraulic connections between them are not being significantly modified.	Incision penetrates through the layered Quaternary sequence and into the underlying chalk. Little further erosion is occurring, so the exposed strata and the hydraulic connections between them are not being significantly modified.	Overall topography controls the spatial pattern of small streams and the main river channel. This is stable over time.	The locations of the phreatic surfaces in the unconfined aquifers are controlled both by the overall topography and the layered structure of the Quaternary deposits.	The artesian conditions in the chalk aquifer are controlled mainly by regional influences and not by the local topography.	Pasture is favoured in riparian areas in the river valleys, with arable agriculture favoured higher up the valley sides and on the plateau. Woodland is confined to the more sheltered areas in the valleys, with individual trees and hedgerows (as field boundaries) more characteristic of the plateau.
No significant influence.	No significant influence.	In principle, the resistance of these sediments to erosion is relevant, as is the particle-size distribution and cohesiveness of the eroded material. However, in practice, the ongoing rates of erosion and sedimentation are very low.	**Complex sequence of Quaternary sands and clays with a laterally extensive layered structure, but with connections of high hydraulic connectivity between layers of high hydraulic conductivity otherwise separated by aquitards.**	The interface between the Quaternary deposits and the underlying chalk is not well defined, with later sediments penetrating into the upper weathered zone of the chalk.	The characteristics of the sequence define whether the stream and river channels are recharge or discharge boundaries. The pattern of drainage ditches is also determined by local drainage characteristics of the soils and underlying sediments.	The locations of the phreatic surfaces in the unconfined aquifers are controlled both by the overall topography and the layered structure of the Quaternary deposits. The hydrochemistry of the aquifer waters will be partly determined by the physico-chemical properties of the deposits.	The Quaternary deposits are taken to confine the underlying chalk aquifer, but areas of higher conductivity in these deposits define locations of upwelling and discharge.	Soil texture and drainage influence the use of land for arable agriculture or pasture.
No significant influence.	No significant influence.	No significant influence.	The interface between the Quaternary deposits and the underlying chalk is not well defined, with later sediments penetrating into the upper weathered zone of the chalk.	**Fractured chalk**	No significant influence of the geology on surface drainage systems, except that the chalk will constitute a discharge boundary for parts of the main river channel.	Indirect connectivity to perched aquifers through the overlying Quaternary sediments.	Defined the porosity and hydraulic conductivity of the confined aquifer and also conditions the hydrochemistry of the groundwater.	No significant influence.
No significant influence.	No significant influence.	Very limited ongoing fluvial incision and sedimentation.	Very limited ongoing fluvial incision and sedimentation.	Very limited ongoing fluvial incision and sedimentation of the exposed chalk in the river valley.	**Agricultural drainage ditches and small ephemeral streams draining to a single river channel.**	The surface water system is connected to the perched aquifers. Both recharge of these aquifers and discharge from them will occur. The hydrochemistry of the perched aquifers will be partly determined by the hydrochemistry of the recharging water.	The surface water system is directly connected to the chalk aquifer in the river valley. It will mainly receive water discharged from the aquifer, so its main influence on the aquifer will be to perturb the flow field in the region of discharge rather than to alter its hydrochemistry.	Closely integrated with the agricultural practices in the area, e.g. by determining the adequacy of drainage of the field system.
No significant influence.	No significant influence.	No significant influence.	No significant influence.	No significant influence.	The surface water system is connected to the perched aquifers. Both recharge of these aquifers and discharge from them will occur. The hydrochemistry of the surface water system will be partly determined by the hydrochemistry of the discharging water.	**Perched aquifers in the Quaternary sediments.**	Hydraulic connections that mainly result in discharges from the chalk aquifer to the overlying perched aquifers, so its main influence on the aquifer will be to perturb the flow field in the region of discharge rather than to alter its hydrochemistry.	Used to extract limited amounts of water from shallow wells for human and animal drinking water and for garden irrigation.
No significant influence.	No significant influence.	No significant influence.	No significant influence.	Will have played a part in defining the existing porosity of the rock through solution effects, but not now resulting in significant changes with time.	The surface water system is directly connected to the chalk aquifer in the river valley. It will mainly receive water discharged from the aquifer, so the river flow rate will be affected (defining base flow) and the hydrochemistry of river waters will also be influenced.	Hydraulic connections that mainly result in discharges from the chalk aquifer to the overlying perched aquifers. This will influence both the geometry of those aquifers and their hydrochemistry.	**Confined artesian aquifer in the chalk.**	Used to extract substantial quantities of water for commercial agricultural irrigation.
Minor influence through differential evapotranspiration from different crop types.	Minor influence through differential evapotranspiration from different crop types.	Stabilises the system against erosion and provides organic matter inputs to soil.	Stabilises the system against erosion.	No significant influence.	Fertiliser additions influence the composition of surface waters. The drainage system is maintained as an integral part of agricultural activities.	Abstraction of water results in drawdown of the water table.	Abstraction of water perturbs the flow system and may result in the introduction of oxygen into the aquifer by penetration down the borehole.	**Mixed agriculture (grain, green and root vegetables, cattle pastures)**

Figure B.4: Illustrative Interaction Matrix for Lowland Britain

The interaction matrix shown in Figure B.4 goes beyond a listing of processes linking the various lead diagonal elements, as it briefly describes the key considerations determining the interactions, recognises important indirect effects and notes interactions occurring at the regional scale, as appropriate. With this additional narrative detail, the information content of even a relatively small (9×9) matrix becomes substantial and it is appropriate to consider alternative forms of presentation. Although more repetitious, a table form, such as Table B.2, may be more readily scrutable.

Table B.2: Illustrative Interaction Matrix for Lowland Britain

Source of Influence	Receiver of Influence	Influence
Köppen-Trewartha climate state DO (temperate oceanic)	Low to moderate levels of atmospheric pollution. Generally low dust loads. Limited influence of marine aerosols (inland site assumed).	Determines seasonal temperatures and precipitation. Relative humidity generally relatively high. Most precipitation falls as rain rather than snow.
	Subdued topography. V-shaped river valleys incised to a depth of a few tens of metres and sometimes penetrating through the Quaternary sediments to the underlying Chalk.	Precipitation-induced incision, but at a very low rate, as river profiles are close to equilibrium. Negligible rates of incision on interfluves.
	Complex sequence of Quaternary sands and clays with a laterally extensive layered structure, but with connections of high hydraulic connectivity between layers of high hydraulic conductivity otherwise separated by aquitards.	No significant influence on structures, as ground freezing is of negligible importance.
	Fractured chalk	No significant influence.
	Agricultural drainage ditches and small ephemeral streams draining to a single river channel.	Seasonal temperatures and precipitation define flow rates in all components of the surface-water system. The baseflow in the main river channel is determined by longer-term variations in climate, being governed by discharge from the chalk aquifer.
	Perched aquifers in the Quaternary sediments.	Seasonal temperatures and precipitation govern the water content of soils and perched aquifers. Relatively wet summers mean that only limited drying of soils occurs in the summer months.
	Confined artesian aquifer in the chalk.	Seasonal temperatures and precipitation govern the recharge of the chalk aquifer from areas close to local interfluves, but the main recharge of this aquifer occurs at a broader regional scale.
	Mixed agriculture (grain, green and root vegetables, cattle pastures)	Seasonal temperatures and precipitation determine a moderate irrigation requirement in some, but not all, years.

Table B.2: Illustrative Interaction Matrix for Lowland Britain (Continued)

Source of Influence	Receiver of Influence	Influence
Low to moderate levels of atmospheric pollution. Generally low dust loads. Limited influence of marine aerosols (inland site assumed).	Köppen-Trewartha climate state DO (temperate oceanic)	No significant influence.
	Subdued topography. V-shaped river valleys incised to a depth of a few tens of metres and sometimes penetrating through the Quaternary sediments to the underlying Chalk.	No significant influence.
	Complex sequence of Quaternary sands and clays with a laterally extensive layered structure, but with connections of high hydraulic connectivity between layers of high hydraulic conductivity otherwise separated by aquitards.	No significant influence.
	Fractured chalk	No significant influence.
	Agricultural drainage ditches and small ephemeral streams draining to a single river channel.	No significant influence
	Perched aquifers in the Quaternary sediments.	Influence on hydrochemistry negligible compared with the effects of agricultural practice.
	Confined artesian aquifer in the chalk.	Influence on hydrochemistry negligible compared with the effects of agricultural practice.
	Mixed agriculture (grain, green and root vegetables, cattle pastures)	No significant influence.

Table B.2: Illustrative Interaction Matrix for Lowland Britain (Continued)

Source of Influence	Receiver of Influence	Influence
Subdued topography. V-shaped river valleys incised to a depth of a few tens of metres and sometimes penetrating through the Quaternary sediments to the underlying Chalk.	Köppen-Trewartha climate state DO (temperate oceanic)	Minor differences in climate between the river valleys and the more exposed plateau into which they are incised.
	Low to moderate levels of atmospheric pollution. Generally low dust loads. Limited influence of marine aerosols (inland site assumed).	Minor differences in pollution and dust loads between the valleys and the plateau.
	Complex sequence of Quaternary sands and clays with a laterally extensive layered structure, but with connections of high hydraulic connectivity between layers of high hydraulic conductivity otherwise separated by aquitards.	Incision penetrates through the layered Quaternary sequence and into the underlying chalk. Little further erosion is occurring, so the exposed strata and the hydraulic connections between them are not being significantly modified.
	Fractured chalk	Incision penetrates through the layered Quaternary sequence and into the underlying chalk. Little further erosion is occurring, so the exposed strata and the hydraulic connections between them are not being significantly modified.
	Agricultural drainage ditches and small ephemeral streams draining to a single river channel.	Overall topography controls the spatial pattern of small streams and the main river channel. This is stable over time.
	Perched aquifers in the Quaternary sediments.	The locations of the phreatic surfaces in the unconfined aquifers are controlled both by the overall topography and the layered structure of the Quaternary deposits.
	Confined artesian aquifer in the chalk.	The artesian conditions in the chalk aquifer are controlled mainly by regional influences and not by the local topography.
	Mixed agriculture (grain, green and root vegetables, cattle pastures)	Pasture is favoured in riparian areas in the river valleys, with arable agriculture favoured higher up the valley sides and on the plateau. Woodland is confined to the more sheltered areas in the valleys, with individual trees and hedgerows (as field boundaries) more characteristic of the plateau.

Table B.2: Illustrative Interaction Matrix for Lowland Britain (Continued)

Source of Influence	Receiver of Influence	Influence
Complex sequence of Quaternary sands and clays with a laterally extensive layered structure, but with connections of high hydraulic connectivity between layers of high hydraulic conductivity otherwise separated by aquitards.	Köppen-Trewartha climate state DO (temperate oceanic)	No significant influence.
	Low to moderate levels of atmospheric pollution. Generally low dust loads. Limited influence of marine aerosols (inland site assumed).	No significant influence.
	Subdued topography. V-shaped river valleys incised to a depth of a few tens of metres and sometimes penetrating through the Quaternary sediments to the underlying Chalk.	In principle, the resistance of these sediments to erosion is relevant, as is the particle-size distribution and cohesiveness of the eroded material. However, in practice, the ongoing rates of erosion and sedimentation are very low.
	Fractured chalk	The interface between the Quaternary deposits and the underlying chalk is not well defined, with later sediments penetrating into the upper weathered zone of the chalk.
	Agricultural drainage ditches and small ephemeral streams draining to a single river channel.	The characteristics of the sequence define whether the stream and river channels are recharge or discharge boundaries. The pattern of drainage ditches is also determined by local drainage characteristics of the soils and underlying sediments.
	Perched aquifers in the Quaternary sediments.	The locations of the phreatic surfaces in the unconfined aquifers are controlled both by the overall topography and the layered structure of the Quaternary deposits. The hydrochemistry of the aquifer waters will be partly determined by the physico-chemical properties of the deposits.
	Confined artesian aquifer in the chalk.	The Quaternary deposits are taken to confine the underlying chalk aquifer, but areas of higher conductivity in these deposits define locations of upwelling and discharge.
	Mixed agriculture (grain, green and root vegetables, cattle pastures)	Soil texture and drainage influence the use of land for arable agriculture or pasture.

Table B.2: Illustrative Interaction Matrix for Lowland Britain (Continued)

Source of Influence	Receiver of Influence	Influence
Fractured chalk	Köppen-Trewartha climate state DO (temperate oceanic)	No significant influence.
	Low to moderate levels of atmospheric pollution. Generally low dust loads. Limited influence of marine aerosols (inland site assumed).	No significant influence.
	Subdued topography. V-shaped river valleys incised to a depth of a few tens of metres and sometimes penetrating through the Quaternary sediments to the underlying Chalk.	No significant influence.
	Complex sequence of Quaternary sands and clays with a laterally extensive layered structure, but with connections of high hydraulic connectivity between layers of high hydraulic conductivity otherwise separated by aquitards.	The interface between the Quaternary deposits and the underlying chalk is not well defined, with later sediments penetrating into the upper weathered zone of the chalk.
	Agricultural drainage ditches and small ephemeral streams draining to a single river channel.	No significant influence of the geology on surface drainage systems, except that the chalk will constitute a discharge boundary for parts of the main river channel.
	Perched aquifers in the Quaternary sediments.	Indirect connectivity to perched aquifers through the overlying Quaternary sediments.
	Confined artesian aquifer in the chalk.	Defined the porosity and hydraulic conductivity of the confined aquifer and also conditions the hydrochemistry of the groundwater.
	Mixed agriculture (grain, green and root vegetables, cattle pastures)	No significant influence.

Table B.2: Illustrative Interaction Matrix for Lowland Britain (Continued)

Source of Influence	Receiver of Influence	Influence
Agricultural drainage ditches and small ephemeral streams draining to a single river channel.	Köppen-Trewartha climate state DO (temperate oceanic)	No significant influence.
	Low to moderate levels of atmospheric pollution. Generally low dust loads. Limited influence of marine aerosols (inland site assumed).	No significant influence.
	Subdued topography. V-shaped river valleys incised to a depth of a few tens of metres and sometimes penetrating through the Quaternary sediments to the underlying Chalk.	Very limited ongoing fluvial incision and sedimentation.
	Complex sequence of Quaternary sands and clays with a laterally extensive layered structure, but with connections of high hydraulic connectivity between layers of high hydraulic conductivity otherwise separated by aquitards.	Very limited ongoing fluvial incision and sedimentation.
	Fractured chalk	Very limited ongoing fluvial incision and sedimentation of the exposed chalk in the river valley.
	Perched aquifers in the Quaternary sediments.	The surface water system is connected to the perched aquifers. Both recharge of these aquifers and discharge from them will occur. The hydrochemistry of the perched aquifers will be partly determined by the hydrochemistry of the recharging water.
	Confined artesian aquifer in the chalk.	The surface water system is directly connected to the chalk aquifer in the river valley. It will mainly receive water discharged from the aquifer, so its main influence on the aquifer will be to perturb the flow field in the region of discharge rather than to alter its hydrochemistry.
	Mixed agriculture (grain, green and root vegetables, cattle pastures)	Closely integrated with the agricultural practices in the area, e.g. by determining the adequacy of drainage of the field system.

Table B.2: Illustrative Interaction Matrix for Lowland Britain (Continued)

Source of Influence	Receiver of Influence	Influence
Perched aquifers in the Quaternary sediments.	Köppen-Trewartha climate state DO (temperate oceanic)	No significant influence.
	Low to moderate levels of atmospheric pollution. Generally low dust loads. Limited influence of marine aerosols (inland site assumed).	No significant influence.
	Subdued topography. V-shaped river valleys incised to a depth of a few tens of metres and sometimes penetrating through the Quaternary sediments to the underlying Chalk.	No significant influence.
	Complex sequence of Quaternary sands and clays with a laterally extensive layered structure, but with connections of high hydraulic connectivity between layers of high hydraulic conductivity otherwise separated by aquitards.	No significant influence.
	Fractured chalk	No significant influence.
	Agricultural drainage ditches and small ephemeral streams draining to a single river channel.	The surface water system is connected to the perched aquifers. Both recharge of these aquifers and discharge from them will occur. The hydrochemistry of the surface water system will be partly determined by the hydrochemistry of the discharging water.
	Confined artesian aquifer in the chalk.	Hydraulic connections that mainly result in discharges from the chalk aquifer to the overlying perched aquifers, so its main influence on the aquifer will be to perturb the flow field in the region of discharge rather than to alter its hydrochemistry.
	Mixed agriculture (grain, green and root vegetables, cattle pastures)	Used to extract limited amounts of water from shallow wells for human and animal drinking water and for garden irrigation.

Table B.2: Illustrative Interaction Matrix for Lowland Britain (Continued)

Source of Influence	Receiver of Influence	Influence
Confined artesian aquifer in the chalk.	Köppen-Trewartha climate state DO (temperate oceanic)	No significant influence.
	Low to moderate levels of atmospheric pollution. Generally low dust loads. Limited influence of marine aerosols (inland site assumed).	No significant influence.
	Subdued topography. V-shaped river valleys incised to a depth of a few tens of metres and sometimes penetrating through the Quaternary sediments to the underlying Chalk.	No significant influence.
	Complex sequence of Quaternary sands and clays with a laterally extensive layered structure, but with connections of high hydraulic connectivity between layers of high hydraulic conductivity otherwise separated by aquitards.	No significant influence.
	Fractured chalk	Will have played a part in defining the existing porosity of the rock through solution effects, but not now resulting in significant changes with time.
	Agricultural drainage ditches and small ephemeral streams draining to a single river channel.	The surface water system is directly connected to the chalk aquifer in the river valley. It will mainly receive water discharged from the aquifer, so the river flow rate will be affected (defining base flow) and the hydrochemistry of river waters will also be influenced.
	Perched aquifers in the Quaternary sediments.	Hydraulic connections that mainly result in discharges from the chalk aquifer to the overlying perched aquifers. This will influence both the geometry of those aquifers and their hydrochemistry.
	Mixed agriculture (grain, green and root vegetables, cattle pastures)	Used to extract substantial quantities of water for commercial agricultural irrigation.

Table B.2: Illustrative Interaction Matrix for Lowland Britain (Continued)

Source of Influence	Receiver of Influence	Influence
Mixed agriculture (grain, green and root vegetables, cattle pastures)	Köppen-Trewartha climate state DO (temperate oceanic)	Minor influence through differential evapotranspiration from different crop types.
	Low to moderate levels of atmospheric pollution. Generally low dust loads. Limited influence of marine aerosols (inland site assumed).	Minor influence through differential evapotranspiration from different crop types.
	Subdued topography. V-shaped river valleys incised to a depth of a few tens of metres and sometimes penetrating through the Quaternary sediments to the underlying Chalk.	Stabilises the system against erosion and provides organic matter inputs to soil.
	Complex sequence of Quaternary sands and clays with a laterally extensive layered structure, but with connections of high hydraulic connectivity between layers of high hydraulic conductivity otherwise separated by aquitards.	Stabilises the system against erosion.
	Fractured chalk	No significant influence.
	Agricultural drainage ditches and small ephemeral streams draining to a single river channel.	Fertiliser additions influence the composition of surface waters. The drainage system is maintained as an integral part of agricultural activities.
	Perched aquifers in the Quaternary sediments.	Abstraction of water results in drawdown of the water table.
	Confined artesian aquifer in the chalk.	Abstraction of water perturbs the flow system and may result in the introduction of oxygen into the aquifer by penetration down the borehole.

Once the GBI has been described in terms of an interaction matrix, such as that illustrated in Figure B.3 and Table B.2, it can be analysed more fully in terms of the geometrical relationships of the individual components, the spatially distributed properties of those components and the processes through which the various components affect their properties, either within a component or as a consequence of interactions between components.

B.1.3 Stage 3: Characterisation of the Geosphere-biosphere Interface

An interaction matrix developed as described in Section B.1.2 provides a basis for a description of the GBI that is suitable for use in developing a mathematical model of the sub-system. This requires consideration not only of the components of the sub-system, but also their geometry, their spatially distributed properties and the processes that operate within and between them. Following from the steps of the assessment process identified in Section 4 of the report on the first workshop [BIOPROTA, 2013], but limiting those steps such that they are appropriate to a single system state rather than a complete narrative of the future development of the GBI, the following sequence is identified.

Step 5a Define the local climate that will exist over the period for which the GBI is to be modelled;

Step 5b Define the local landforms that will be present over the period for which the GBI is to be modelled. This includes both their topography and their lithostratigraphy, since the two are intimately related.

Step 5c Characterise the unperturbed surface-water and groundwater flow regime that would apply under the specified climatic and landform characteristics.

Step 5d Characterise the unperturbed hydrogeochemical regime that would apply under the specified climatic and landform characteristics, and with the specified surface-water and groundwater flow regime.

Step 5e Characterise the unperturbed thermal regime that would apply under the specified climatic and landform characteristics, and with the specified surface-water and groundwater flow regime.

Step 5f Specify how human actions are assumed to perturb the system.

Step 5g Define the spatial and temporal pattern of radionuclide fluxes that would enter the GBI over the period for which it is to be modelled. This needs only to be done to the extent that it influences the way in which the mathematical model of the GBI would have to be formulated in order to utilise that spatial and temporal pattern as input.

Step 5h Define the outputs that are required from the GBI, e.g. spatially and temporally variable radionuclide fluxes to the biosphere or concentrations in environmental media such as soils and surface-water bodies.

Once steps, 5a to 5h have been completed (including iterations between them to achieve self consistency, as required), it will be possible to provide a conceptual description of the GBI from which a mathematical model can be developed, or against which an existing mathematical or computational model can be audited in terms of its fitness for purpose (see below). Having developed such a model, it will be possible to perform the following activities (which lie outside the scope of the methodology).

- Calculate the transport of fluxes of radionuclides entering the GBI in order to estimate either output fluxes to the biosphere or output concentrations in environmental media.
- Calculate radiation doses and other measures of radiological impact (a step that lies outside the development and application of a model for the GBI).

In the following, consideration is given to how steps 5a) to 5h should be undertaken in practice for each of the GBIs that need to be addressed in each scenario developed as part of the assessment process.

Step 5a: Defining the Local Climate

The local climate can seldom be defined more closely than in terms of a Köppen-Trewartha climate state. However, for assessment modelling of the hydrological and hydrogeological aspects of the GBI, temperature and precipitation data will be required. For the representation of potential future climatic conditions, it will not be possible to specify these data very precisely. Previously [BIOCLIM, 2004], mean monthly values of temperature and precipitation were taken from analogue stations with long-term climate records. It seems appropriate to continue to apply this approach, though it is noted that more comprehensive, model-based approaches are now being developed within the context of MODARIA WG6. It is noted that the analogue stations have to be selected with care, since they should be appropriate to the geographical and landscape context of the site of interest. Thus, for example, for

Lowland Britain analogue stations from continental west-coast locations in mid-latitudes and at altitudes of less than 200 m are preferred.

From the mean-monthly temperature and precipitation values together with limited assumptions concerning the effects of different soil and vegetation types on evapotranspiration, assessments can be made of the annual hydrologically effective rainfall (relevant to computing the water balance for the area of interest) and of the summer soil moisture deficit (relevant to irrigation requirements). For a local area, it will generally be adequate to define temperature, precipitation and other, climate-related variables each as a single time series applying to the entire area. However, if there is substantial local variability in factors such as altitude and aspect, it may also be necessary to define spatial variations in each of the relevant quantities. These spatial variations may, typically be expressed in variations from the mean value for the area. Also, whereas for many calculations, the use of long-term averages of the various quantities will be appropriate, in some cases it will be appropriate to take into account the inter-annual variations that are recorded in the records from the analogue stations or are simulated by climate models. For example, it may be appropriate to calculate the summer soil moisture deficit on a year-by-year basis in order to determine the fraction of years that would give rise to an irrigation requirement under a specific irrigation scheme.

It should also be kept in mind that several relevant analogue stations will normally be identified. Consideration will have to be given as to whether the individual station records should be lumped to yield a single composite record to be propagated through the assessment, or whether the data from the individual stations should be propagated through the assessment, with lumping occurring in the results of the assessment calculations rather than in the inputs to those calculations. In either approach, further judgements will have to be made as to how the detailed records from the stations should be averaged temporally (e.g. daily, monthly or seasonally) in order to provide robust statistics appropriate for use in a long-term assessment context.

Step 5b: Defining Local Landforms

As noted in the introduction to Section B.1.3, this includes both the overall topography and the lithostratigraphy. Where a site has been selected, such a characterisation would typically comprise a 3D visualisation of the topography and lithostratigraphy either of the existing landscape or of the landscape evolved under particular assumptions. Even if a generic assessment is being undertaken, it will generally be appropriate to develop an illustrative 3D visualisation of the landscape, so that a suitable abstraction of that landscape can be made for modelling purposes. It is emphasised that the visualisation of the landscape in 3D is for the purposes of conceptual model development. It does not imply that the mathematical model to be derived from that visualisation would necessarily be 3D. This would depend on the assessment context and the degree of homogeneity both in the landscape and in the pattern of radionuclide releases to the GBI for which the assessment was to be undertaken.

Although the GBI may not extend to the ground surface, e.g. the biosphere may be defined to comprise soils and sub-soils and may require a radionuclide flux at the base of the subsoil, it will generally be appropriate to define local landforms from the surface to a depth in the bedrock below the interface with the geosphere component of the system. In this way it will be ensured that the GBI is consistently embedded within the wider modelling framework. Although formally the local atmosphere may be included in the GBI, it will seldom be necessary to represent it as a spatially distributed entity within the GBI. Thus, it can generally be excluded from the 3D visualisation of the landscape and be reported only in terms of its typical characteristics.

The 3D visualisation of the landscape will usually comprise a set of components, each with a well-defined geometrical extent and arranged in a space-filling arrangement, such that there are no gaps in that arrangement between the ground surface and the base of the representational domain within the lateral extent over which that representational domain is defined. Each of those components will be defined by a set of properties. Those properties would be defined in terms of parameter values or parameter value distributions at the mathematical model stage. However, for developing a conceptual model, it is sufficient to recognise the types of properties that would be required to characterise each component. In the GBI, it is probably sufficient to recognise the following types of components:

- Biota;
- Terrestrial soils and sediments;
- Aquatic sediments;
- Organic deposits in mires;
- Hard rock between fractures;
- Fractures in hard rock.

In general, both terrestrial soils and sediments and aquatic sediments can be characterised as porous media that can be represented hydrologically using parameters such as the total porosity, transport porosity, tortuosity, constrictivity, and both hydraulic conductivity and matric potential as functions of water content (unless the soil/sediment can be taken to remain saturated throughout the period for which the GBI is to be simulated). However, they also need to be characterised in terms of texture, mineralogy and organic matter content, so that these factors can be taken into account when developing a conceptual model of the hydrogeochemistry and radionuclide transport properties of the included pore waters. It is noted that pore systems may exist at various scales within soils and sediments (including intra-grain, inter-grain and macropores, such as root channels) and that these various pore systems may need to be separately recognised in the conceptual model.

In the case of organic deposits in mires, it may again be possible to characterise the material hydrologically as a porous medium. However, in this case, greater emphasis will be placed on the structure and decomposability of the organic material than on the mineralogy of sediment particles.

In the case of hard rock (including all types of rock that are subject to significant fracturing), a distinction is made between hard rock between fractures and fractures with their mineral infills. However, it should be recognised that this distinction is not absolute. The fractures and their fracture infills are recognised as larger identifiable components of the GBI. However, between them, the rock will be fractured at smaller scales, so the hard rock between fractures will include both the porosity of matrix pores and the porosity of micro-fracturing of the system. Nevertheless, the distinction is useful, as the rock between the fractures can typically be characterised as a porous medium, as described above, whereas the fractures themselves must be treated quite differently.

In terms of flow, individual fractures can be characterised in terms of their geometry and a spatially variable fracture aperture (allowing for the possibility of channelled flow through fracture systems). Fracture systems also need to be characterised in terms of their connectivity, as flow can occur only through connected fracture networks. In terms of radionuclide transport, consideration also needs to be given to the types and amounts of fracture minerals that are present, as radionuclides can diffuse into, and sorb to, such fracture minerals. They may also have to diffuse through such fracture minerals before entering the rock matrix, where they can be retarded by diffusion into, and sorption within, dead-end pore systems.

Step 5c: Defining the Unperturbed Surface-water and Groundwater Flow Regime

To a large extent, the climate and topography will define the surface-water and groundwater flow domains, though account may also have to be taken of regional sources of surface water and groundwater. Thus, for example, if a river passes through the modelled domain, account will have to be taken of the upstream source of water in this river and the downstream loss of water in this river from the domain. Similarly, if the domain is underlain by a regional aquifer, then both discharge from and recharge to this regional aquifer within the model domain will need to be taken into account. At the conceptual modelling stage, the aim is only to describe the overall pattern of surface-water and groundwater flows within the GBI domain, rather than to quantify those flows. However, it is recognised that it may be necessary to undertake some quantitative flow or water-balance modelling in order to obtain the insights necessary for developing a conceptual model of the flow system, e.g. to determine those areas that constitute discharge zones and those that constitute recharge zones at different seasons of the year.

In defining the groundwater flow regime, the information required is primarily the hydrological properties of the materials present in the domain and the geometrical relationships of those materials to each other. To this information must be added information on the local climate, which is necessary for estimating both surface water flows and infiltration. Finally, surface water and groundwater flows across the lateral boundaries of the modelled domain need to be established from information available at a regional scale.

The surface-water and groundwater flow regime is defined as that appropriate to the unperturbed state. Definition of this state is not unambiguous, as it necessarily takes account of the pattern of land use in the local area. Here it is defined as meaning that no wells are present in the local domain of the GBI and that no large-scale engineered hydrological structures (such as dams or reservoirs) are present. If such features are currently present, then account must be taken of their perturbing effects when defining the postulated unperturbed flow regime. The reason for adopting this approach is that such perturbing features may not be present in the future at times of relevance to the assessment. Of course, if these features are considered to be relevant to the assessment process they can be restored at step (f).

Step 5d: Defining the Unperturbed Hydrogeochemical Regime

The hydrogeochemical regime may be defined mainly by observations or by model simulations in which waters of different types are mixed in the GBI domain and react with the various types of solid that are present. Although model simulations may be undertaken at this stage, the main aim is to characterise the spatial distribution of different water types present in pore and fracture spaces in the sediments and rocks that are present in the domain. As with the flow regime, it is the unperturbed state that is considered, so the modifying effects of existing perturbations due to wells and large-scale engineered hydrological structures have to be allowed for so as to characterise the unperturbed situation. In addition, any large-scale chemical perturbations, e.g. due to contamination, should also be allowed for, but this does not include effects such as typical fertiliser additions associated with the specified land use (if that land use is similar to that at the present day).

Pore and fracture waters will typically be defined in terms of their major and trace element composition, and in terms of other derived quantities such as pH and redox potential. At the conceptual stage, it is likely to be appropriate to describe these waters as broad types, rather than give detailed compositions. An important aspect of the conceptual model will be the spatial distributions of these different water types relative to the various solid media that are present.

It should be noted that the process of developing the hydrogeochemical model may identify aspects of the hydrological and hydrogeological model that need to be updated. Thus, there may be a degree of iteration between items (c) and (d). Such iterations may also involve the acquisition and interpretation of additional data in order to resolve inconsistencies or ambiguities identified in the process of model development.

Step 5e: Defining the Unperturbed Thermal Regime

In the GBI, radioactive decay heat originating from the repository is unlikely to be a significant consideration. Therefore, the thermal regime will be largely determined by the interplay of climate conditions and geothermal heat production (characterised by the vertical temperature gradient that exists in the crust of the Earth). In broad terms, the types of thermal regime to be considered include unfrozen, seasonal ground freezing, discontinuous permafrost with taliks and continuous permafrost with taliks. Where permafrost is present, there will also be an overlying active layer that is subject to freeze-thaw processes.

In the active layer, there will be a need to characterise seasonal fluctuations in temperature and extent to which the water present in that layer will be frozen or unfrozen. As freezing will affect the hydraulic properties of the material and the freezing point will be influenced by the chemical composition of the pore and fracture water, the thermal regime will have a strong influence on the hydrogeological and hydrogeochemical regimes. Therefore, it will be appropriate to have the thermal regime in mind when defining those hydrogeological and hydrogeochemical regimes. This applies even more strongly when permafrost regimes are under consideration, as these will result in reorganisation of the groundwater flow system at a regional scale relative to that which would exist in unfrozen conditions. Nevertheless, detailed consideration of the thermal regime is placed in sequence after the hydrogeological and hydrogeochemical aspects of conceptual model development. This is because it is primarily determined at the regional scale (and hence provides part of the context for the totality of conceptual development of the GBI), whereas here the consideration is its conceptual model implications at a local scale. This emphasises that all stages of conceptual model development relating to the GBI take place within a predefined regional context.

Step 5f: Perturbations due to Human Actions

Once an unperturbed system is fully defined, it is possible to impose potential human actions upon it. In general, these human actions will comprise the construction and utilisation of water wells and boreholes constructed for other purposes (such as the exploitation of geothermal energy). Injection boreholes may also need to be considered, although these would typically introduce water to considerable depth (e.g. in fracking or in recycling of geothermal water after heat extraction) and might not significantly influence the GBI). Other large-scale human activities may also need to be considered, e.g. quarrying or reservoir construction and utilisation. However, general land-use in the sub-model domain would not need to be considered, as this would be addressed in the conceptual model of the unperturbed system.

It is anticipated that the relevant human actions would be prescribed in the scenario under consideration and would be strongly determined by the assessment context. Thus, in the context of developing a conceptual model of the GBI, the emphasis is on characterising the effects of such perturbations and not in justifying the types of perturbations to be considered.

In general, when considering the effects of human actions, the same sequence can be considered as in defining the unperturbed system, i.e. the first consideration is effects on the geometry of the system (topography and lithostratigraphy), then the effects on hydrology and hydrogeology, and finally effects on hydrogeochemistry. Effects on the thermal regime may need to be considered outside this sequence. For example, if large-scale ground thawing were to occur, this would need to be considered before effects on hydrology and hydrogeology were addressed.

Step 5g: Spatial and Temporal Patterns of Radionuclide Flux

The preceding steps will result in a 3D description of the GBI. This provides a context for specifying the spatial and temporal pattern of radionuclide flux entering that sub-system, generally across its bottom boundary. That radionuclide flux will generally be provided by a model of the deeper part of the geosphere. However, the spatial domain of that model may overlap with that of the GBI, so the flux to be extracted may come from an internal surface within the geosphere model, rather than from its upper boundary. In addition, the flux may not be fully characterised in space and time, e.g. it may be a time-dependent flux arising from a 1D (stream tube) representation of the geosphere. If this is the case, additional assumptions may have to be made in order to map it onto a spatially extensive boundary. Alternatively, the lack of spatially distributed information may be a consideration in determining the structure and dimensionality of the model of the GBI.

Step 5h: Outputs from the Model of the Geosphere-biosphere Sub-system

Outputs from the GBI will typically be either radionuclide fluxes used as input by a biosphere model or radionuclide concentrations in environmental media. In either case, spatially distributed values are likely to be required.

Step 6: Defining the Dimensionality and Structure of the Conceptual Model

Having defined the GBI in 3D through steps 5a to 5h it is appropriate to give consideration to the dimensionality in which it needs to be modelled and the structure of the model at the selected dimensionality. Elsewhere [BIOPROTA, 2013], it has been identified that the dimensionality can be as follows.

- Zero dimensional representation (compartmental) whereby a set of objects are linked by flows. This approach allows some understanding of the spatial aspects of the system to be preserved. Where there has been a large degree of aggregation then it is likely that assumptions on homogeneity will be required resulting in essentially a zero-dimensional approach. However, there is a continuity between zero dimensional and higher dimensional approaches. For example, for a soil column, a series of layers could be represented as a set of well-mixed compartments resulting in an essentially 1-dimensional approach.
- 1-dimensional models (typically vertical profiles).
- 2-dimensional models. These can be either horizontal, for example 2-dimensional aquifer models that allow transmissivity to be evaluated and are particularly useful also for surface water flows, or 2-dimensional vertical models that are useful for hill-slope analyses.
- 3-dimensional full catchment-scale models. These are generally considered to be the gold standard, but can become heavy with regard to computational requirements. It may therefore be appropriate to first understand the system using 2-dimensional models and then move to a 3-dimensional representation, as required.

Models of different dimensionality can be mixed to give hybrid models.

The dimensionality of the adopted model will depend on the characteristics of the GBI and also on the assessment context. For example, if the assessment context only requires spatially averaged radionuclide concentrations in environmental media, then a lower dimensionality may be appropriate than if there is a requirement to define peak concentrations in space and the spatial extent of concentrations that are more than a particular fraction of those peak concentrations.

The dimensionality of the model can also depend on how the radionuclide flux entering the model domain is defined. For example, if the input flux is spatially distributed over a relatively homogeneous domain (such as the base of a deep agricultural soil directly overlying a bedrock aquifer that is modelled as part of the geosphere), then a 1D vertical model of the soil may be appropriate to map that flux into radionuclide concentrations at the soil surface (though sub-horizontal transport in the soil column may have to be represented as a loss process from the system) or a 2D hillslope model may be used to explicitly include downslope transport to a river channel. In contrast, if the input flux is defined without any information on its spatial extent (as with a stream tube representation of the geosphere) then a 3D model of the GBI may be required to map that input flux to a spatially distributed output flux. This might be appropriate if it was considered that most of the dispersion and dilution of the radionuclide plume occurred within the GBI.

Within the framework of the adopted dimensionality, the various components of the model need to be identified. These can be spatially distinct, e.g. topsoil and subsoil, or spatially co-extensive, e.g. rock matrix solids and pore water within the rock matrix. It is these components that provide the context for determining the importance of various processes within the GBI.

Step 7: Process Identification and Importance Specification

From application of the methodology described above, a 3D descriptive model of the GBI would be obtained, together with an evaluation as to how that 3D model should be represented geometrically (i.e. in terms of dimensionality) when implemented in a mathematical model. Furthermore, the key characteristics of the components of that model (e.g. porosity of the rock, chemical composition of pore and fracture waters, temperature of the rock) would have been identified. On the basis of this 3D descriptive model and its geometric representation, it will be appropriate to move on to identify the processes relating those characteristics that need to be included in the model. In identifying the processes, it is helpful to characterise them under the following headings:

- hydrological and hydrogeological;
- geochemical;
- thermal;
- mechanical (e.g. erosion and deposition; freezing-induced stresses);
- biotic (microbiological, macrofloral and macrofaunal);
- nutrient and/or energy based.

Some indication of the types of processes of relevance will already have been obtained at the sub-system description step. However, that analysis will have been undertaken at a general descriptive level. At this later step in the methodology, the system is more precisely defined both geometrically and in terms of the spatial domains occupied by the individual components. Thus, process identification and importance evaluation (Step 7a) can be undertaken more precisely.

In addition, if a changing GBI is being represented, it will be appropriate to take into account both natural events and human-induced perturbations.

It is emphasised that the identified processes are taken to be relevant across the whole GBI domain, though their significance will vary between different parts of that domain (for example freezing and thawing will be important in the active layer of a permafrost regime, but will not be of importance at greater depths where the sediments remain permanently frozen). Thus, process identification leads to a list of processes that have to be assessed for significance to components of the domain. For example, bioturbation may be assessed as having a high significance in topsoil, a moderate significance in subsoil, and low significance in unconsolidated Quaternary deposits underlying the subsoil. Thus, process identification results in a list of processes of relevance for inclusion in the mathematical model, together with an evaluation of their significance in the various components of the geosphere-biosphere sub-model domain.

Having identified the processes and their significance, consideration can be given to their degree of coupling (Step 7b). The first stage is to develop an interaction matrix with the components of the GBI as diagonal elements and the processes of relevance as off-diagonal elements. An illustration for a fractured hard-rock aquifer is shown in Figure B.5.

Rock Matrix	Desorption				
Sorption	**Pore waters in the rock matrix**		Diffusion		Diffusion
		Altered rock adjacent to fractures	Desorption		
	Diffusion	Sorption	**Pore waters in the altered rock**		Diffusion
				Fracture minerals	Desorption/ Dissolution
	Diffusion		Diffusion	Sorption/ Precipitation	**Fracture water**

Figure B.5: Illustrative Interaction Matrix for Processes relevant to Radionuclide Transport in Fractured Hard Rock

Note that the interaction matrix does not aim to illustrate all the processes that relate these components in fractured hard rock. Rather, it is specifically targeted at those processes that influence radionuclide transport. Alternative matrices could be drawn up to represent other aspects of the system, e.g. heat transport. Also, the matrix combines elements that are spatially distinct with elements that are spatially co-extensive. For those elements that are spatially co-extensive (solids and their included waters) the relevant processes are sorption and desorption (plus precipitation and dissolution in the fractures, where the possibility exists of incorporating radionuclides in fracture minerals or subsequently releasing them). For waters in different components, radionuclides can be transported between them by diffusion. In a more complex representation, distinct parts of the fracture system might be represented separately.

In such a case, advective transport between the different parts of the fracture system would need also to be included.

In broad terms, the degree of coupling between different components of the system may be considered to range from weak to strong. The strength of the coupling, the timescale over which it operates and its directionality (i.e. whether it operates only from component A to component B or whether it also operates from component B to component A, described as unidirectional and bidirectional, respectively) determine how it should be represented in mathematical modelling. Alternative approaches are for models of the relevant processes to be uncoupled, loosely coupled or tightly coupled. In Figure B.5, the processes of sorption and desorption act bi-directionally on short timescales, so they are considered to require tight coupling (indicated by the thick solid boundaries in the figure). In contrast, diffusion between the various water components, although bidirectional, is a slower process and can be represented by a looser coupling (indicated by the dashed boundaries). Although there could be areas of the fractures without altered rock allowing diffusion directly from the fracture water to the pore waters in the rock matrix, such areas are considered of little significance, so the fractures are considered not to be coupled directly to the rock matrix (they are, of course, indirectly coupled through the altered rock).

B.1.4 Summary of the Methodology

The various steps set out in the previous sub-sections taken together provide an overall methodology for characterising the GBI at a level of detail appropriate for underpinning development of a mathematical model of the sub-system. The overall methodology is summarised in Table B.3 (see also Figure B.1).

Table B.3: Summary of the Methodology for Developing a Conceptual Model of the Geosphere-biosphere Sub-system

Step	Description	Relevant Figure
1	Determine whether the assessment context pre-defines the GBI. If not, identify and justify, in broad terms, the components of each GBI of relevance.	B.1a
2a	Determine whether environmental change needs to be taken into account in defining the GBI. If so, propagate global and regional changes to the local level.	
2b	Interpret the combined effects of these changes at a local level in terms of narratives describing qualitatively different futures.	
3	Examine each narrative to determine the preferred approach to representing environmental change (i.e. sequential or non-sequential) and determine the states and transitions to be represented.	
The following steps apply to each state for which a conceptual model is to be developed.		
4	Develop an interaction matrix showing the interactions between the components of the GBI.	B.1b
5	Characterise the GBI in a 3D descriptive model.	
5a	Define the local climate.	
5b	Define local landforms.	
5c	Define the unperturbed surface-water and groundwater flow regime.	
5d	Define the unperturbed hydrogeochemical regime.	
5e	Define the unperturbed thermal regime.	
Iteration of steps 5c to 5e may be required to achieve a self-consistent description of the unperturbed system.		
5f	Define perturbations of the system due to human actions.	B.1b
5g	Define the spatial and temporal flux of radionuclides into the 3D descriptive model of the sub-system developed in Step 6.	
5h	Define the outputs required from the model of the GBI.	
6	Specify the dimensionality and components of the model of the GBI (these components are more detailed than those identified at Step 1).	
7a	Identify the processes operating within and between the components specified in Step 9 and evaluate their significance in relation to the individual components and the interactions between them.	
7b	Determine how the components of the GBI should be coupled to each other on the basis of the processes operating within and between them.	

Thus, the outputs from application of the methodology comprise:

- Narratives of the development of the GBI in qualitatively different futures (Step 3);
- For each narrative, a set of 3D descriptions of the GBI with each description corresponding to a particular state of the GBI (Step 5);
- For each description corresponding to a particular state of the GBI, an identification of the detailed components of that sub-system, a determination of the processes operating within and between them, an evaluation of the significance of those processes in relation to the individual components and the interactions between them, and an evaluation of how the components should be coupled to each other in a mathematical model of the sub-system (Steps 6 and 7).

B.1.5 Development of a Conceptual Model for a Transition between States

The methodology described above deals in detail with the characterisation of time-invariant states of the GBI. In many assessment contexts, this may be all that is required, because radionuclide residence times in the GBI are short compared with the timescale for substantial changes to that sub-system. However, there will be contexts in which the time-development of the GBI is a significant consideration. To address this, a similar approach to that adopted in BIOCLIM [2004] is proposed. Time-invariant states before and after the transition of interest are fully characterised using the methodology summarised in Table B.3. These states are characterised in terms of detailed components, and the processes operating within and between those components. Components of the sub-system prior to and after the transition are matched to each other. In some cases, there will be a one-to-one correspondence between those components, but this will not always be the case, e.g. if the transition involves emergence of a land area from the sea or the conversion of a lake to a mire. Where there is not a one-to-one correspondence, a judgement will have to be made as to how the components present prior to the transition map onto those present subsequent to the transition.

Once a mapping between the components before and after the transition has been completed, the transformations of each of the components can be examined in turn to identify the events and processes that have given rise to the transition. Many of the processes identified are likely already to be represented in the descriptions of the individual states. Thus, for example, erosion and sedimentation may be represented within a state because they affect radionuclide transport. However, in the context of a transition between states they will be identified through their effects on altering the geometry and properties of components of the GBI. Also, additional processes may be identified that are specific to the transition. These additional processes can then be included along with the processes associated with each state to provide a conceptual model of the transition. Note that the additional processes are identified because of their action in transforming the components of the GBI, but that they are included in the conceptual model of the GBI both because they transform the sub-system by performing the mapping described earlier and because they can act as additional radionuclide transport processes during the transition.

Whereas, the conceptual models for states relate to radionuclide transport through a time-invariant environment, the conceptual models for transitions represent radionuclide transport through a changing environment.

B.2 ILLUSTRATIVE SCENARIOS AND GEOSPHERE-BIOSPHERE SUB-SYSTEMS ASSOCIATED WITH THOSE SCENARIOS

During the first workshop on the project, it was agreed that up to four scenarios would be addressed as illustrations of how the methodology set out in Section B.1 could be applied in practice. It was further identified that the first of these scenarios should be based on assessments recently undertaken by SKB and Posiva in order to gain maximum knowledge from the experience gained in undertaking these assessments. It was also proposed that a lowland landscape subject to fluvial processes, as exemplified by Lowland Britain, should be represented. Finally, it was proposed that a semi-arid variant of the lowland landscape applicable, for example, to Spain, should also be included. These three scenarios are taken forward in this Briefing Note. They are described in outline in this section, but more detail is provided in Section B.3, where Step 3 of the methodology is applied to two of those scenarios (for Forsmark and Lowland Britain) to produce detailed narratives describing the futures associated with each scenario [BIOPROTA, 2013][a]. The descriptions provided here include narratives describing qualitatively different futures (Step 3 of the methodology set out in Table B.3) and were developed within specific assessments contexts in which it was accepted that it was necessary to take environmental change into account (Steps 1 and 2 of the methodology set out in Table B.3)

[a] Only limited information was available for Central Spain and it was felt that detailed analysis of this scenario would add little to the analysis undertaken for Lowland Britain.

B.2.1 Site-specific Scenario for a Hard Rock Site

The SKB and Posiva assessments both extend out to one million years after closure, but quantitative radiological impacts are only assessed by Posiva for the first ten thousand years. In both cases, repeated glacial-interglacial cycles are addressed in the modelling. As studies relating to the Forsmark site are fully documented in a comprehensive safety assessment that has been submitted to the regulatory authorities in support of SKB's license application to construct and operate a final repository for spent nuclear fuel [SKB, 2011 and references therein], information relating to that site has been used in scenario definition. Relevant information relating to the current characteristics of the site and projected future changes to the regional and local environment are presented in Appendix A (Section A.3).

Basis for identifying Geosphere-biosphere Sub-systems applicable at Forsmark

The description of future changes in the environment at Forsmark set out in Section A.3 indicate that study of a single glacial-interglacial cycle modelled on the Weichselian and starting at the present day will form a sufficient basis for defining the full range of GBIs that could occur at that site. Furthermore, this range of sub-systems will be relevant to the proposed Finnish facility at Olkiluoto, as this is located in a very similar geological and geographical context on the eastern shore of the Baltic at similar latitude to Forsmark (see Appendix A).

B.2.2 Generic Scenario for a Lowland Temperate Site

Various landscape evolution scenarios have been developed by the Radioactive Waste Management Directorate (RWMD) of the Nuclear Decommissioning Authority (NDA) for the British Isles, focusing on lowland landscapes. The emphasis has been on inland landscapes for two reasons. First, impacts of releases to terrestrial environments are orders of magnitude larger than impacts of the same releases to estuarine or marine environments, due to the much larger degree of initial dilution occurring in the latter contexts. Secondly, assessments of impacts in shoreline environments would depend on details of the characteristics of both the geosphere and biosphere and cannot readily be evaluated in a generic context. Thus, consideration of radiological impacts in coastal environments has been deferred for future consideration, as required [NDA, 2010b], though a model for estuarine and coastal environments has been developed (Walke *et al.*, 2013).

The future pattern of climate evolution for Lowland Britain adopted by RWMD was based on a rule-based downscaling of the BIOCLIM [2004] scenarios that included a protracted period of warm interglacial conditions extending from the present day to several tens of thousands of years into the future. The sequences of climate states adopted are shown in Figure B.6.

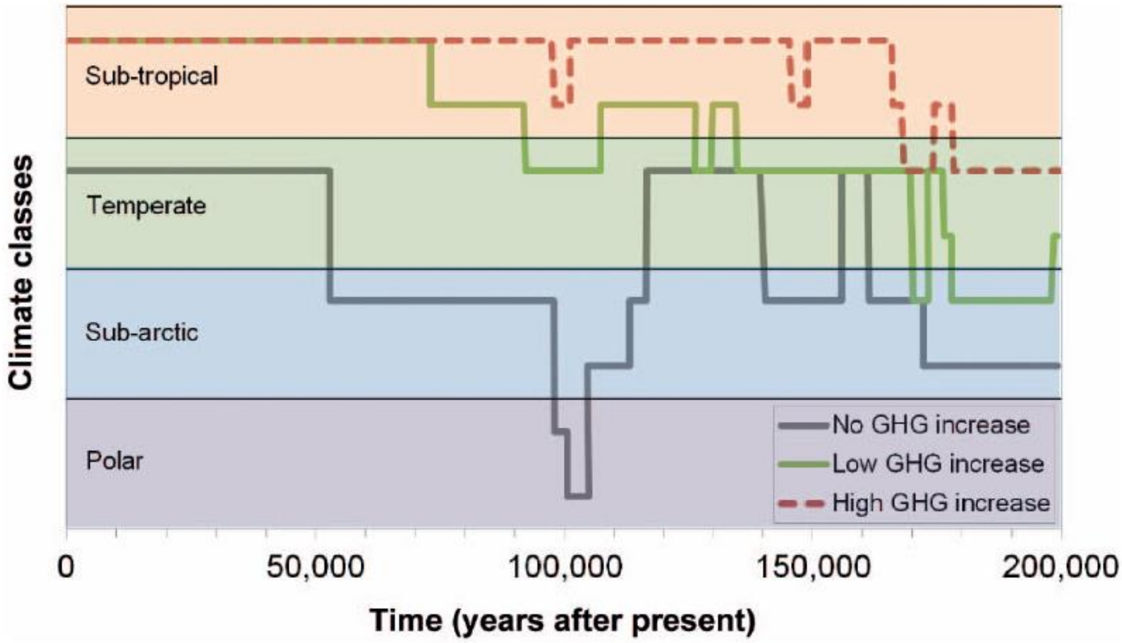


Figure B.6: Sequences of Future Climate States for Lowland Britain (from Walke *et al*., 2012)

Illustrative patterns of landscape evolution [NDA, 2010b] are shown in Figures A.1 and A.2.

For the generic scenario, it is proposed that the landscape development sequence shown in Figure A.1 should be adopted. The drier, sub-tropical conditions shown in Figure A.2 are appropriately addressed in the semi-arid scenario described in Section B.2.3.

B.2.3 Generic Scenario for a Lowland Semi-arid Site

This scenario is based on that developed for Spain in BIOCLIM [2004].

At the present day, the typical climate class for Central Spain (using the Köppen-Trewartha scheme) is CSa (temperate with dry and warm summers and winter rain; known as the Mediterranean climate).

The near-surface lithostratigraphy, from the south of the Sistema Central range to the Campos de Calatrava area is dominated by Lower Palaeozoic formations, mainly shales and sandstones, but profoundly eroded to the point of constituting a peneplain. However, limestones dominate to the south of Badajoz. Also, intrusive granitic formations are common. The topography has been affected by extensional processes. It comprises upland and lowland, with subdued landforms intersected by fluvially incised river valleys on the granitic zones. Surface water bodies are mainly flowing rivers, with some reservoirs located on the main rivers. The main soil groups represented are cambisols, lithosols and fluvisols.

The climax vegetation is represented by *Quercetum ilicis* Mediterranean evergreen forest, but it has been extensively degraded by long-term human actions. Today it has been substituted by bush and steppe vegetation (*Stipa tenacissima*, *Lygeum starpum*, *Cistus ladaniferus*, *Juniperus communis*). Agricultural soils occupy 39% of the total area, with 17% irrigated; grassland represents 13% of the total area with 3% irrigated; forest represents 32% of the total area with none irrigated; and other uses represent 16% of the total area.

Under the BIOCLIM [2004] low greenhouse gas scenario, a rapid transition in climate is expected over the next 300 years to climate class BWh, which is without previous representation in the palaeoclimatic record of the Iberian Peninsula, characterised by a mean annual temperature in the range 32-33ºC, compared with about 14.5ºC at the present day. This would be followed by a moderately rapid cooling transition over 5 ka to 27.2-28ºC (climate state BWh/BSh, also not represented in the palaeoclimatic record) and then a sequence of cooling and warming transitions out to 200 ka AP. Overall, it seems that, for almost all of the next 120 ka, the climatic characteristics of Central Spain are likely to lie outside the climatic conditions recorded in the palaeoclimatic record. For about 67 ka, they will be even warmer than the mean annual temperature of 18ºC thought to have been attained in the Atlantic period from 5.4 to 6.6 ka BP (the Holocene thermal optimum). For this reason, it was necessary to look for climatic analogue stations and environmental analogue locations outside the Iberian Peninsula, including those relating to climate types As (tropical), BSh (warm dry steppe) or BWh (hot desert) depending on the evolution of the atmospheric humidity.

The lowest mean annual temperature to be reached during the next 210 ka was assessed to be 8.8 to 8.0ºC (climate class DC, BWk or BSk), previously experienced during the Younger Dryas, Oldest Dryas, Middle-Final Würm, Eowürm and Mèlisey II (BSk/BWk).That situation is expected at about 175 ka AP.

Based on the above analysis, the following main situations were identified as requiring consideration.

Situation 1: From Csa to BWh

This comprises a rapid transition over about 300 years during which mean annual temperatures in Central Spain will increase from about 14.5°C to between 32 and 33°C. Annual mean precipitation values will decrease to about 200-330 mm per year, and the precipitation will occur mainly in summer.

Both the high temperatures and limited precipitation imply a markedly arid environment. These changes in climate would apply to a landscape with soils and sediments, and topography essentially unchanged from that at the present day. Surface runoff and interflow could either increase or decrease relative to the present day. However, it seems highly likely that stream and river flows would decrease, with some smaller streams becoming ephemeral. Due to the aridity, soils would be expected to lose cohesion. Aeolian weathering would be increased, but no substantial changes in topography would be expected in only 300 years. Vegetation may be mostly or entirely absent in some regions, as vegetation is very rare in hot dry deserts, such as those of North Africa. Any plants that are present will almost all be ground-hugging shrubs and short woody trees. Decreased precipitation will probably imply a reduction in groundwater resources. Reservoir construction for surface-water storage might be undertaken by human communities to ensure better capture of summer precipitation for subsequent use. The increased aridity would also result in an increased soil moisture deficit during the growing season (between April and October). On the basis of data from analogue meteorological stations, the mean monthly moisture deficit in June would be more than 400 mm; annual mean moisture deficit values could be as large as 2418 mm. This would result in a much increased irrigation demand. With irrigation, a wide range of crops could be grown, as at the present day. Human community characteristics would be driven by the limited water availability, with communities being concentrated in the vicinity of sites of exploitation of deep groundwater resources and close to new reservoirs on the main rivers.

Situations 2 and 3: From BWh to BWh/BSh

The main transition is expected to take place between 0.3 and 5 ky AP. The resultant dry climate that then persists for a period of about 75 ka is classified as semi-arid (BSh). The cooling transition sees mean annual temperatures fall from about 27.2 to 28°C to about 21°C during the lengthy BSh period. The analysed BS meteorological stations have mean annual precipitation values of between 144 mm and 879 mm. Averaged over stations, the mean annual precipitation is 521 mm, with a difference in mean monthly values of almost 100 mm between the driest month (February) and the wettest (August).

Over this protracted period, upland zones can be lowered due to prolonged (80 ka) and increased chemical weathering relative to Situation 1. Surface runoff will be increased relative to BWh conditions and landscape slopes will be reduced. Intense rainfall with short duration, as is observed under present BWh climates in Spain, will result in more active soil erosion. Cambisol development will be restricted and leptosol development will be enhanced. Vegetation cover and standing biomass will be increased relative to Situation 1, with development of shrub and herb vegetation, and deciduous or evergreen broadleaf trees present only in patches (as there is not enough precipitation for trees to grow except by rivers). Increased precipitation will probably imply an increase in groundwater resources.

Reservoirs for surface-water storage might be developed by human communities to ensure better capture of summer precipitation for subsequent use, as in Situation 1. The increase in precipitation would also result in a decreased soil moisture deficit during the growing season.

On the basis of data from analogue meteorological stations, the mean monthly moisture deficit would reach a maximum of 290 mm in May. This would result in a lower irrigation demand than in Situation 1. The cold winter and summer drought reduce the growing season to three or four months (between April and July). Winter cereal crops (77 % of which are not irrigated) and un-irrigated pasture grasses are the most common types of agriculture developed under current BS climates in Spain. The steppe climate tends to go in cycles, where there may be ten years or more of good rains followed by as many years of drought. In order to be able to cope with this climate, people used to be nomadic. However, now they rely on deep wells and irrigation systems. Nevertheless, the climate is still too harsh for large cities and industries to develop. Overall, human rural communities can be characterised as similar to those at present day, with a low overall density of population.

Situations 4 and 5: From BSh to Cs

This involves a cooling transition over a period of about 10 ka at the beginning of a total period of 26 ka over which Csa and Csb conditions will occur. Cs states imply climate characteristics corresponding to those currently dominant in Central Spain. The Cs type is typically Mediterranean, being a hybrid between maritime Mediterranean with mild winters (Csa) and continental Mediterranean with cold winters (Csb). The state is often characterised by a dry summer. Winter is in general the period with the largest amount of precipitation. The analysed Spanish stations record a mean annual precipitation of 522 mm, with an average range in the mean monthly precipitation of almost 60 mm between the driest month (July) and the wettest (December).

The climate would apply to a landscape with a lower topography than at present due to earlier changes. Surface runoff would be increased relative to the BSh state, as is observed today. Vegetation is likely to be much as at the present day. The holm forest, which develops on any soil type, mainly in plains, and cork trees, which develop easily on silica soils, will be associated with various vegetation layers; the most common are evergreen, small-leaved bushes, as well as other perennial plants. Such bushes are very common under Cs climate conditions. Based on data from analogue meteorological stations, the mean monthly moisture deficit would reach a maximum of 170 mm in July. This would result in an irrigation demand similar to that at present. With irrigation, a wide range of crops could be grown, as at the present day. Also, there is no reason why animal husbandry practices and human community characteristics should be very different from those at the present day.

Situation 6: From BSh to DC or BWk/BSk

This is a cooling transition to temperate conditions, taking around 20 ka, with expected mean annual temperatures of between 8 and 9ºC. Also, monthly minimum temperatures are expected to be below 0ºC.

Precipitation is likely to range between 425 and 525 mm per year, with the minimum monthly precipitation being around 25 mm. The annual moisture deficit/excess, based in the analyzed stations, is between a deficit of 99 mm and an excess of 383 mm.

The climate would apply to a landscape with a reduced topography relative to present conditions, due to earlier changes. Surface runoff would be increased relative to BSh conditions, as is currently observed. Vegetation is likely to be grassland and scrub woodland, with some development of forest. Based on data from analyzed meteorological stations, the mean moisture deficit reaches a maximum of only 99 mm in summer. This would result in an irrigation demand much lower than in the current situation. There is no reason why animal husbandry practices should be very different from those at the present day. Overall, with a similar or better pattern of agriculture to that at the present day, there is no climate-driven reason to propose any substantial change in human community characteristics.

B.3 CONCEPTUAL MODELS OF THE GEOSPHERE-BIOSPHERE INTERFACE

B.3.1 Hard Rock Site at Forsmark

Assessment Context and Components of the Geosphere-Biosphere Sub-system

The assessment context is set out in Table B.4 with additional information on key aspects being provided subsequently.

Forsmark is the location of an operational facility for short-lived radioactive waste (SFR) in addition to being the proposed location for a repository for spent nuclear fuel. Whilst information is derived from studies relating to both repositories, the primary focus of this illustrative assessment is the deep geological repository for spent nuclear fuel as documented in the safety assessment SR-Site [SKB, 2011] and related publications.

Table B.4: Summary of the Assessment Context

Aspect of the Assessment Context	Summary of the Characteristics of this Aspect of the Assessment Context
Purpose of the assessment	Site-specific safety assessment to evaluate the safety of a potential KBS-3 repository at Forsmark and investigate whether the KBS-3 method has the potential of fulfilling regulatory safety criteria at the Forsmark site, given the level of knowledge on important conditions and processes in the host rock and in the surface system after completion of the surface-based site investigations.
Endpoints of the assessment	Radiological impacts on an individual representative of the most exposed group and radiation exposure of wildlife populations.
Assessment philosophy	Cautiously realistic. Estimations of the radiological risk for humans and the environment are as realistic as possible, and, as far as possible, based on conditions measured at the site and application of the substantial knowledge of present-day conditions at Forsmark and its past Holocene history. However, cautious assumptions are applied in terms of future human behaviour and land use to maximise exposure.
Repository system	A KBS-3 type geological disposal facility whereby copper canisters with a cast iron insert containing spent nuclear fuel are surrounded by bentonite clay and deposited at approximately 500 m depth in groundwater saturated, granitic rock.
Site context	The Forsmark site is located on the coast of the Baltic Sea in the county of Uppland within the municipality of Östhammar, about 120 km north of Stockholm, Sweden. The planned repository area covers approximately 2×2 km, and is situated immediately southeast of the Forsmark nuclear power plant close to the present-day shoreline. The area is subject to post-glacial uplift that, together with a flat topography, results in rapid shoreline displacement.
Source term	Failure of single disposal canister with radionuclides being released to groundwater that migrates to the biosphere through a discrete fracture network.
Time frames for assessment	Safety assessment required for 1 million years after closure with detailed risk analysis for the first 1,000 years. Quantitative risk analysis required for the period up to 100,000 years after closure. In the period after 100,000 years, it should be demonstrated that releases from both engineered and geological barriers are limited and delayed as far as reasonably possible using calculated risk as one of several indicators.
Societal assumptions	There are no prescriptive assumptions regarding future human behaviour and land use.

The disposal concept is illustrated in Figure B.7.

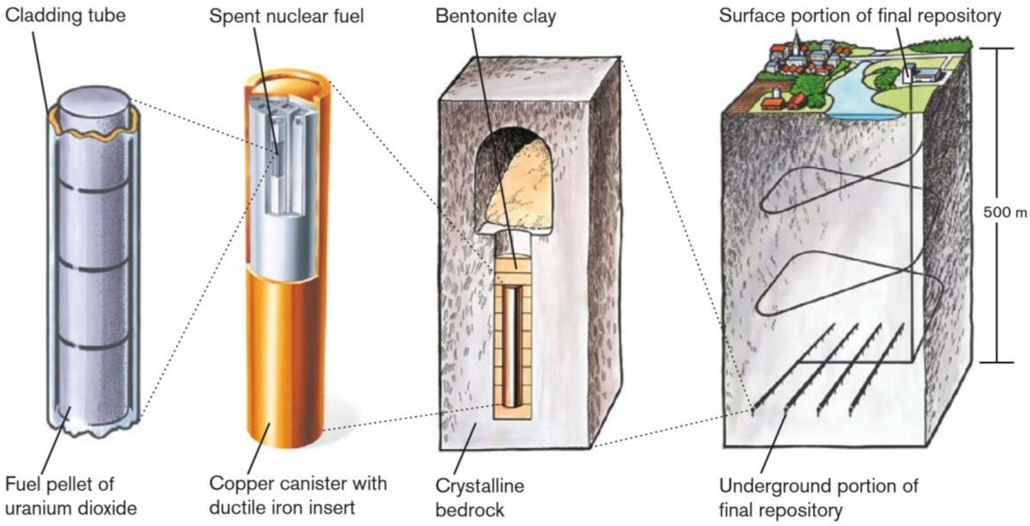


Figure 3-1. *The KBS-3 concept for storage of spent nuclear fuel.*

Figure B.7: The KBS-3 disposal concept [reproduced from SKB, 2010]. Copper canisters with a cast iron insert containing spent nuclear fuel are surrounded by compacted bentonite clay and deposited at approximately 500m depth in groundwater saturated granitic rock.

Forsmark is a coastal area situated in the south western part of the Fennoscandian Shield in northern Uppland, in the municipality of Östhammer. The area is characterised by a topography of low relief: the most elevated areas are some 25m above current sea level and the area as a whole is located below the highest coastline associated with the last glaciation, having emerged from the Baltic Sea over the last 2,000 years, with the first parts of the area emerging around 500 years BC. The fast rate of shoreline displacement has resulted in a young terrestrial system that contains a number of recently isolated lakes and wetlands, and new lakes are continuously formed as a consequence of the regressing shoreline. The coastline consists of sheltered shallow bays and small islands in an archipelago setting. The marine areas have a gentle slope towards the northwest and a deep trough runs in the north-south direction in the eastern part of the embayment. The lowest point (-55m elevation) is located in the northern part of this trough. The majority of the coastal area has a sea depth of 10 m or less. The seabed in the coastal areas is dominated by erosion and transport bottoms with heterogeneous sediments, consisting mainly of sand and gravel with varying fractions of glacial clay.

Southern Sweden has a Cfb climate according to the Köppen-Trewartha (or Köppen-Geiger) classification; it is a warm temperate humid climate with the warmest month on average being lower than 22°C and an average of four or more months above 10°C. The mean annual air temperature at Forsmark itself is approximately 7°C and the vegetation period, at which the air temperature remains above 5°C, lasts approximately from May to September. The region shows a strong precipitation gradient in the east-west direction. The annual precipitation in the Forsmark area is about 546 mm a^{-1}, which is lower than the 30 year long-term mean precipitation of 690 mm a^{-1} at 15 km west of the Forsmark area, but higher than the 490 mm a^{-1} at a similar distance north-east of Forsmark. On average, snow covers the ground for 105 and 80 days per season on forest land and open land, respectively, and the period of snow cover is typically from the end of November until the beginning of April. The maximum snow depth recorded at the site is 48 cm in forest land and 25 cm in open land, and the maximum snow water content is 144 and 64 mm, respectively. Measurements of ground frost penetration during three seasons (2003/04–2005/06) showed that ground frost was present for 40 and 80 days/season in forest land and open land, respectively. The maximum ground frost depth was 0.46 m on open land, and only 0.08 m on forest land.

The major part of the landscape is covered by a thin regolith layer with a mean depth in the Forsmark area of c. 4 m. Exposed bedrock and bedrock with only a thin regolith layer (<0.5 m) occupy c. 9% of the area. The major portion of regolith at Forsmark is glacial deposits, reworked during multiple glaciations and relocated by subsequent glacial and post-glacial processes. The upper part of the regolith is affected by deposition and decomposition of organic material, and in terrestrial areas also by weathering of the original material, thus forming soil in terrestrial areas and sediments, often rich in organic matter, in aquatic areas.

Approximately 90% of the ground surface in the Forsmark area consists of regolith that originates from the last glaciation when the ice sheet reworked and redistributed sediments of earlier Quaternary glaciations. The distribution of regolith is typical of areas in Sweden below the highest postglacial coastline. Elevated parts of the terrain are dominated by till or exposed bedrock and valleys have a higher percentage of clay and post-glacially re-deposited fine-grained material. Till constitutes the dominant regolith exposed at the ground surface, occupying approximately 65% of the terrestrial surface areas and 30% of the area currently submerged by the sea. Generally, the till is thicker in depressions, thus levelling out some of the bedrock relief. The till in the Forsmark area is subdivided into:

1) a sandy till with medium frequency of superficial boulders (dominant),
2) a clayey till with low boulder frequency, and
3) a sandy till with high boulder frequency.

Clay, gyttja clay, sand and peat occur frequently, but in scattered deposits, mainly covering smaller patches. Peat accumulation occurs in all Forsmark wetlands, but deposits thicker than 0.5 m are restricted to the south-western part of the area. This is the most elevated part of the Forsmark area and has, therefore, experienced terrestrial conditions and peat accumulation for the longest time.

The infiltration capacity of the regolith generally exceeds rainfall and snowmelt intensities, and groundwater recharge is dominated by precipitation and snowmelt: monitoring has indicated that most groundwaters from the Quaternary deposits are of meteoric origin.

The groundwater table in the Quaternary deposits is generally shallow (within 1 m of the ground surface) and follows the ground-surface topography. The small-scale topography results in shallow, local groundwater flow systems in the Quaternary deposits that overlie larger-scale flow systems in the bedrock. The lakes are generally the recipients of groundwater discharge for most of the year although intense evapotranspiration during the summer lowers groundwater levels and some lakes may periodically switch to becoming recharge areas.

The underlying bedrock consists of crystalline rock that formed between 1,850 and 1,890 million years ago during the Svecokarelian orogeny, and it has been affected by both ductile and brittle deformation. The ductile deformation has resulted in large-scale ductile high-strain zones and the brittle deformation has given rise to large-scale fracture zones. Tectonic lenses, in which the bedrock is much less affected by ductile deformation, are enclosed between the ductile high strain zones.

Shoreline displacement that has occurred since the last glaciation has had a major impact on the distribution and relocation of fine-grained Quaternary deposits with the most exposed areas being affected by wave washing and bottom currents. This has resulted in the erosion of sand and gravel from older deposits that have been transported and deposited at more sheltered locations. Glacial clay and other fine-grained deposits have been, and continue to be, eroded from more sheltered locations during periods of erosion. As a result of these processes, till is the most dominant type of Quaternary deposit, occupying around 65% of the surface in terrestrial areas and 30% of the sea bottom, whereas clay occurs primarily in depressions on the sea bottom and below present lakes.

Shoreline displacement continues to be an important process in the area. Combined with the flat topography, this results in the transformation of the coastal sea bed into new terrestrial areas or shallow freshwater lakes depending upon the topographical conditions. Such lakes are the dominant surface water features in the area, ranging in size from 0.03 to 8.67 km^2, with a mean depth ranging from 0.1 to 1 m.

The lakes are hard water oligotrophic lakes that are slightly alkaline, with low total phosphorus and high concentrations of major ions, resulting in a high electrical conductivity. This is a combined effect of the calcium-rich Quaternary deposits, recent emergence from the Baltic Sea and the shallow lake depths that results in high primary production at the sediment surface and very low production in the water column itself. The high productivity plus deposition of material from the surrounding catchment ultimately leads to lake infilling and peat formation. The ultimate fate of lakes is therefore either to be transformed into wetlands or drier terrestrial land areas. Wetlands cover 25% or more of some sub-catchments and are mostly coniferous forest swamps or open mires.

The marine ecosystem in the Forsmark area is relatively productive due to upwelling along the mainland. The water of the Baltic Sea is brackish and, in the Forsmark area, has a salinity of around 5‰. During high-sea-level events, seawater occasionally flows into coastal freshwater lakes.

Human activities, especially over the past millennium when agriculture was introduced, have also played an important role in defining the terrestrial ecosystem. The introduction of agriculture has reduced the area of land covered by forest and resulted in wetlands being drained to make way for the production of agricultural land. The extent of agricultural land has decreased since the 1950's due to abandonment of former open land which has allowed a gradual return to a more forested landscape (predominantly Scots pine and Norway spruce). Latterly, in the last few decades, land use changed to allow for the establishment of the Forsmark nuclear power plant that transformed parts of the area from relatively pristine rural conditions to an industrial park and a semi-urban society. The remaining area is sparsely populated and there are no permanent residents in a 20 km^2 area along the coast. Current land use is dominated by forestry, including hunting. The major food supply for people around Forsmark is, as in the rest of society, obtained primarily from general dealers, which means that it is produced at distant farms. From the period from the last glaciation until around 500 BC, the whole area was submerged below the sea.

Site investigations indicate that major earthquakes have not occurred in the Forsmark area during the Quaternary period and overall the area shows relatively little seismic activity.

With the assessment context requiring a 1 million year assessment timescale and with climate exerting a large influence on the GBI, a range of climatic conditions of relevance to repeated glacial cycles must be taken into account in terms of identifying and justifying the components of the geosphere biosphere sub-system. These are identified and justified in relation to the specific assessment context for the Forsmark site in Table B.5.

Table B.5: Geosphere-Biosphere Sub-system Components for Forsmark

Geosphere-biosphere Sub-system Component	Component Description in the Assessment Context	Justification
Climate and atmosphere	The climate will range from current temperate conditions through to full glacial conditions with significant periods of periglacial conditions. Due to the effects of ice-sheet formation, including isostatic depression, submergence of the area around the site below the Baltic Sea will occur, with an initial onset occurring around 65,000 years after present (AP). The initial change from the current temperate to periglacial conditions is anticipated to occur around 8,000 years AP. The 120,000 year glacial cycle is assumed to repeat over the assessment timeframe.	Glacial cycle based on study of the last glacial cycle as reported in SKB (2010).
Geographical extent	Local area of a few square kilometres to a few tens of square kilometres where the radionuclide plume from one or more failed canisters would emerge into the Quaternary sediments. The location of this area is likely to be determined by the more major brittle deformation zones, as these tend to have high hydraulic conductivity.	Based on the spatial extent of the proposed geological disposal facility and the likely degree of dispersion of the plume in the overlying rock.
Location	Coastal site in northern Uppland, Sweden.	Defined in the assessment context.
Topography	Undulating lowland of low relief, below the highest coastline associated with the last glaciation.	See description of Forsmark area given in the text.
Human community	Small rural communities making maximum use of local foods such that only contaminated foods are consumed. Drinking water is consumed in equal amounts from a contaminated well and from surface water in a lake or stream.	From consideration of endpoints of the assessment in the assessment context.
Near-surface litho-stratigraphy	Undulating Quaternary deposits, suggesting large variations in thickness of cover, that are largely comprised of till with post-glacial clay, including clay gyttja, found in deeper parts of valleys and on the sea floor.	Description of the surface system [SKB, 2011, section 4.10.2].
Water bodies	Surface water bodies are small, hard-water shallow, oligotrophic lakes and wetlands with some flowing streams that are subject to drying in summer months. Inflow of brackish water from the Baltic Sea may occur to the most low-lying lakes during very high sea-level events. Lakes act as recharge sources to till aquifers during summer when evapotranspiration from this zone is evident, but at other times receive discharges of deeper groundwater. The regional water table may either be located within the underlying bedrock or within the Quaternary deposits.	See description of Forsmark area given in the text and in SKB [2011, section 4.10.2].
Biota	Largely a forested area (with forests comprising in excess of 70% of the landscape). The forests are dominated by Scots pine and Norway spruce. Wetlands cover between 10 and 20% of the land area. Arable land and grassland are limited, covering less than 5% of the land area. Large game animals such as deer and moose are present and are subject to recreational hunting.	Based on the description of the surface system [SKB, 2011, section 4.10.2].

Propagation of Environmental Change to the Local Level

Following the establishment of the assessment context, step 2 of the methodology requires that consideration be given as to whether environmental change needs to be taken into account in defining the GBI. If so, then global and regional changes have to be propagated to the local level. From the assessment context, it is determined that the range of climatic and related landscape characteristics applicable over the next 1 million years is to be taken into account.

The global and regional changes to be addressed are shown in Figure B.2. Volcanism is not an issue in a Swedish context. Also, orogeny, large meteorite impacts and large seismic events are extremely unlikely to occur in the region of Forsmark within the next 1 million years. Attention is therefore focused on global climate change and the effects of such global climate change on continental ice sheets and global sea level and the influence of these on regional EFEPs as shown in Figure B.2. Both a reference case and a global warming variant have been investigated [SKB, 2011]; however, the latter does not introduce any additional considerations into the definition of the GBI, so only the reference case is considered herein. Future climate change in the reference case is based around the assumption that the next glacial cycle will be similar to the last (the Weichselian) and that this reference climate case, of 120,000 years duration, can be repeated throughout the assessment time window [SKB, 2010; 2011]. The reference glacial cycle, therefore, comprises a repetition of conditions reconstructed from the last glacial cycle. This reconstruction, as reported in SKB [2010], has been made through the application of both global and regional models to investigate ice-sheet development and isostatic response to loading during a glacial cycle and the development of permafrost conditions, and has been supported by geological information. Climate data from the regional model have then been extracted for the Forsmark site. The narrative below therefore focuses on changes at the local level, with differences from the regional setting being made as appropriate.

Climate Regime

According to the Köppen-Trewartha classification system, Sweden has a temperate, moist climate with year-round precipitation; annual precipitation over much of Sweden is between 600 and 800 mm, being heaviest during July-November. The North Atlantic Drift and numerous areas of low pressure produce a climate with winters that are 20-30°C warmer than at corresponding latitudes in Siberia and Canada. Along the coasts of southern Sweden, the climate is warm-temperate, with a mean temperature in July of 15-16°C and a natural cover of deciduous forest. The climate in the rest of the country is cool temperate, the predominate vegetation being coniferous forest. Tundra conditions prevail in the mountains. The duration of summer is greater in the south (5 months) as compared with the north (3 months). As such, the growing season varies considerably over the country, lasting between 210 and 220 days in southernmost Sweden and half of this in the far north. Snow cover in southern Sweden lasts for between 50 and 150 days each winter.

The Forsmark region has a climate that is typical for the Swedish east coast with a mean annual air temperature of 5°C (7°C locally at the site) and an annual mean precipitation of 559 mm. The mean summer temperature is around 15°C and the mean winter temperature is around 4°C [SKB, 2011].

The reference glacial cycle for the region assumes that the current temperate climate persists for several thousand years prior to cooling. Subarctic conditions prevail from around 8.5 ka AP until a return to more temperate conditions from 12-35 ka AP, after which cooler conditions prevail once again. During the subarctic conditions, precipitation will likely be lower than during temperate conditions and permafrost will develop. Such conditions will limit evapotranspiration and the frozen ground will limit infiltration of surface waters.

Glacial conditions are expected to occur with ice-sheet formation in the region from around 60 ka AP. A second larger glaciation period then occurs at around 90-110 ka AP, before returning to temperate conditions similar to those of the present day. The temporal evolution of the various climate domains (temperate, periglacial and glacial) in Southeast Sweden throughout the reference glacial cycle is summarised in Table B.6.

Table B.6: Temporal Evolution of Climate Domains at Forsmark (reproduced from Table 4-6 in SKB [2010])

Climate domain/ submerged conditions	Time (ka after present)	Duration (ka)
Temperate	0-8	8
Periglacial	8-12	4
Temperate	12-35	23
Periglacial	35-58	23
Glacial	58-65	7
Submerged	65-75	10
Periglacial	75-89	14
Glacial	89-111	22
Submerged	111-120	9

Ice-sheets and Glaciers

The Forsmark region is currently unglaciated, but has been subject to glacial conditions, including ice-sheet coverage during the last glacial period. An ice-sheet model simulation of the Weichselian ice sheet has been made [SKB, 2010] through reconstruction of factors such as temperature during the last glacial cycle and the model has been calibrated against the known maximum ice margin positions. The regional ice-sheet behaviour can be characterised as being distinctly dynamic throughout the glacial cycle. Data extracted on ice-sheet thickness for the Forsmark region indicates that there were two phases of ice-sheet coverage, during the cold stadials of MIS 4 and MIS 2. As such, future glacial periods and associated ice-sheet coverage are of considerable importance with respect to future climate and landscape development throughout the assessment timeframe.

In the reference glacial cycle, lowering of air temperature during the onset of the glacial results in ice-sheet inception and the ice-sheet then grows progressively larger in a number of distinct growth phases, with intervening phases of more restricted ice coverage. The earlier periods of ice sheet advancement in Sweden, at around 14,000 and 38,000 years AP do not extend as far south as the Forsmark region. There are thus two periods of ice coverage at Forsmark, at around 60 ka AP and 100 ka AP, the latter being of similar magnitude to the last glacial maximum. Together these equate to Forsmark being covered by ice sheets for a period of around 30,000 years out of the 120,000 year glacial cycle. During the glacial maximum, the ice thickness at Forsmark is expected to be some 2,900 m. The ice thickness during the earlier phase is also significant, reaching around 2,000 m (Figure B.8).

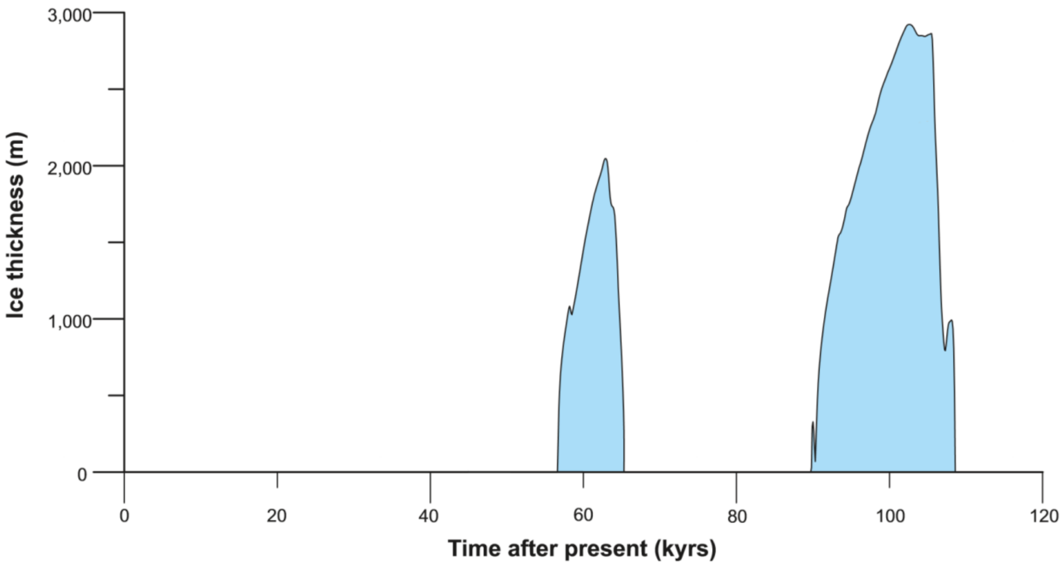


Figure B.8: Development of Ice-sheet Thickness at the Forsmark Site throughout the Reference Glacial Cycle. Figure provided by SKB.

Periods during which the ice margin halts over the site cannot be excluded for Forsmark during ice advance, maximum or retreat phases, given suitable climate conditions. By generalising the development of the last deglaciation, it is postulated that ten temporary halts of short duration and one major halt of long duration, corresponding to the Younger Dryas event, for a deglaciation of a full-sized ice-sheet equivalent to that developed at the last glacial maximum could occur. For short halts, stable ice margin conditions are considered to persist for 200 years whereas for the major still-stand, a completely stable position of the ice margin is pessimistically assumed for 1,000 years.

Permafrost

As climate cools, permafrost, defined as ground where the temperature remains continuously below 0°C for more than two years, develops, which typically requires an annual mean air temperature below -1 to -9°C. Development is from the ground surface with growth downwards as a result of a complex heat exchange across the atmosphere/ground boundary layers, taking account also of the geothermal heat flow from the Earth's interior. In the reference glacial cycle, permafrost occurs in the periglacial climate domain and beneath parts of the ice sheet in the glacial climate domain, although the presence of ice sheets largely serves to protect the ground from cold, thus preventing the development of permafrost to great depths.

In the reference glacial cycle, permafrost conditions start 7,000 years AP. Initially growth is sporadic (spatial coverage less than 50%), but as the climate gets colder, discontinuous permafrost (spatial coverage between 50 and 90%) forms and ultimately continuous permafrost. The maximum depth of permafrost in the reference glacial cycle coincides with the arctic climate that prevails in the region from 50,000 years AP. At this time, the maximum modelled permafrost depth reaches around 260 m at Forsmark. Permafrost stops developing and then starts to slowly diminish when ice sheets cover the area. Permafrost then grows again once the ice sheets have retreated and the ground is re-exposed to a cold climate prior to the second ice sheet developing. The maximum depth of permafrost in the region during this phase is around 180 m.

During periods of permafrost, an unfrozen active layer develops above the permafrost during summer conditions. This active layer is typically 40-70 cm deep, depending upon the vegetation and soil. For a bare surface, the active layer extends to a thickness of around 1 m.

Regional Isostacy

Ice loading during glacial conditions results in land mass depression and, upon retreat of the ice, post-glacial isostatic rebound occurs, as is evident for the current interglacial period. The rate of isostatic rebound is variable. The rate of rebound in Forsmark has decreased from c. 3.5 m/100 years directly after the deglaciation to a present rate of c. 0.6 m/100 years, and it is predicted to decrease further to become insignificant around 30,000 AD. With repeated future glacial periods, regional isostacy will continue to play an important role in landscape evolution.

During the initial phase of the reference glacial cycle, when climate is getting colder and ice sheets are expanding globally, global sea levels fall and the rate of isostatic rebound from the last glacial cycle decreases but remains significant for parts of Fennoscandia. Over the first 30-40 ka of the glacial cycle, isostatic uplift will elevate the Forsmark area to around 70 m above the current sea level and the shoreline will have been displaced several km to the east of the current coastline.

Regional Landform and Sea-Level

Climate has a strong influence on the regional landform, particularly in coastal areas that are dynamic with regard to shoreline displacement. At the time of the latest deglaciation of Forsmark around 8,800 BC, which corresponds to the last part of the reference glacial cycle, the area was covered by approximately 150 m of glaciolacustrine water and the nearest shoreline was situated some 100 km west of Forsmark. Isostatic rebound has subsequently led to shoreline displacement and the raising of the Forsmark area above sea level.

Over the first 30-40 ka of the glacial cycle, isostatic uplift will elevate the Forsmark area to around 70 m above the current sea level and the shoreline will have been displaced several km to the east of the current coastline and many lakes in more inland areas will have been terrestrialised: within the first 1 ka AP, shoreline displacement will result in a horizontal transfer of the coastline to a location c. 1 km east of the repository and some of the coastal bays will become isolated and transformed into lakes. Whilst the Baltic Sea remains connected to the Atlantic, the relative shore-level along the Baltic Sea coast is determined by isostatic rebound and global sea-level change. However, should the two be separated by sea level falling below the Darss Sill in the southern Baltic Sea, then the Baltic Sea will be transformed into a lake, the surface level of which will be determined by the altitude of the contemporary Darss Sill. At the earliest, this is considered to occur at 9,000 years AP.

During the first glaciation at around 60-70,000 years AP, the region is isostatically depressed by the weight of the ice sheet, resulting in the Gulf of Bothnia regaining contact with the southern part of the Baltic Sea. Much of the region will, at this time, be situated below the Baltic Sea water level until around 75 ka AP when isostatic recovery brings the Forsmark region above the Baltic water level once again. The region then remains above sea level and free of ice for approximately 15 ka until, with the onset of the second main phase of glacial conditions at around 100-110 ka AP, the site is again isostatically depressed. In the following deglaciation at around 110 ka AP, the Baltic Sea regains contact with the Atlantic and the Forsmark site is submerged by a saline sea. At the end of the reference glacial cycle, at 120,000 years AP, as isostatic rebound proceeds, the Baltic Sea is transformed to an inland brackish sea, similar to the current situation.

The repeated phases of ice-sheet coverage, deglaciation and submergence will lead to surface denudation in the region. The degree to which denudation occurs will largely be determined by the erosional capacity of the ice sheet and the land topography. Considering the bedrock topography in Forsmark to have been fairly stable throughout the Quaternary glaciations, there is no reason to believe that future glaciations would leave a significantly different imprint on the bedrock topography. It is considered that future denudation in the Forsmark area will be limited to between 1 and 2.6 m per glacial cycle. This results from the flat topography and the low erosional capacity of ice sheets in such a context. This rate of denudation equates to some 8-20 m throughout the entire assessment period. The major part of this denudation (1-2 m per glacial cycle) is a result of glacial erosion, occurring during phases of warm-based ice sheet coverage. The non-glacial denudation occurring in the glacial cycle from all other active erosion and weathering processes during temperate and periglacial climate conditions amounts to 0.6 m. Whilst the landscape that will emerge from a vanishing ice sheet will not be the same as the present time, it will likely show a similar pattern of glacial sediments and minor bedrock basins occupied by lakes.

Land Use, Vegetation and Soils

Climate over the reference glacial cycle will have a dramatic effect on soils, vegetation and future land use.

Shortly after the most recent ice retreat, the landscape was free of vegetation and can be characterised as polar desert. Relatively soon after the deglaciation, ice-free areas were colonised, resulting in a sparse birch forest. Subsequently the climate has oscillated between colder and warmer periods. During the cold Younger Dryas period (11,000-9500 BC), large areas of the de-glaciated parts of Sweden were again affected by permafrost resulting in the disappearance of much of the previously established flora and fauna. From the onset of the Holocene (c. 9500 BC) and thereafter, southern Sweden has been more or less covered by forests, although the species composition has varied with climate and, from 3000 BC, has been affected by the introduction of agriculture which served to open the landscape, reducing the areas covered by forest. A similar effect of climate on plants and animals is envisaged for future climate domains.

In the initial 1 ka AP, land use is expected to be similar to the present time. The potential for sustainable human exploitation of food resources in the area is not expected to differ greatly from the situation today. Only minor parts of the newly formed land will have the potential for cultivation due to the boulder-rich sediments in the former sea and lake areas, but also due to problems with draining the low-elevation new areas. New areas will, however, be available for grazing by livestock. The potential water supply for humans is also expected to be fairly unaltered during this period. In the future, the deep canal north of the repository has potential as a freshwater reservoir when the salinity decreases, and also the stream through Bolundsfjärden may potentially be used for freshwater supply. New wells may be drilled in the bedrock or dug in the regolith in the area that is land today, whereas the new land will be too young for wells if current practises are sustained.

Beyond 1 ka AP, but within the remaining temperate period, shoreline displacement will continue but at a more gradual rate. Much of the newly formed land will be unsuitable for farming due to boulder- and stone-rich deposits, but there are large areas currently submerged in central Öregrundsgrepen with fine-grained sediments that it will be possible to cultivate when exposed on land. Also patches of organic soils on previous lakes/mires may be cultivated, but presumably these soils can be sustainably utilised only for limited periods since compression and oxidation of the organic material will lower the ground surface and cause problems with drainage. The availability of freshwater for human supply is expected to gradually increase during this phase as new lakes and streams will form. These will probably resemble the present-day lakes and streams, and most of the lakes will be short-lived due to their shallowness. New groundwater, potentially useful as drinking water, will be available when the shoreline moves eastwards.

During future temperate climate domains, prior to the onset of glacial conditions, similar biosphere conditions are assumed, with the terrestrial ecosystem consisting of mainly forests and mires, but with agriculture occurring on areas of fine-grained sediments. Higher altitude areas with outcrops of bedrock will be forested with pine. Shallow lakes will be minimal in the region of the repository.

With the onset of periglacial conditions, terrestrial plant productivity will start to decline and will be characterised by more tundra-like vegetation (sedges, herbs and shrubs). However, conditions may vary considerably within this climate domain, from a situation not very different from temperate conditions but with shallow permafrost, to a harsh arctic climate with deep permafrost and very sparse vegetation.

As permafrost conditions start to develop, this will prevent infiltration of meteoric water and, whilst precipitation is likely to be lower than during temperate conditions, combined with lower infiltration this is likely to result in a greater predominance of wetlands dominated by mosses. Their productivity will be lower than under temperate conditions due to the reduction in terrestrial plant productivity. The freeze-thaw process will disturb the soil and render it more exposed to erosion. The lower productivity during periglacial conditions means that the area of land required to sustain a community will be increased.

During glacial periods with ice sheet coverage, terrestrial productivity will be low and permanent residents are unlikely. Whilst terrestrial productivity will be low, a productive aquatic community may be present at ice margins that may be exploited by people and animals, both terrestrial and aquatic. Due to the low food productivity under glacial climate domains, human behaviour is thus likely to be nomadic to allow maximum use of the scarce resources.

As ice sheets regress with the onset of a warmer climate, the region will become inundated by the Baltic Sea as a result of land depression from the ice load combined with rising global sea level. Use of resources during such phases would be limited to utilisation of those from the marine environment. Land then re-emerging from the Baltic as a result of isostatic recovery is likely to develop into a landscape similar to present. However, as noted above, much of the newly formed land will be unsuitable for farming due to boulder- and stone-rich deposits, but areas with finer-grained sediments will be present and suitable for cultivating. Organic soils associated with previous lakes and wetlands may also be cultivated, but the extent will be limited as a result of the compression and oxidation of organic material that will lower the ground surface and cause drainage issues. Land use is thus likely to be dominated by forestry as at the present day.

Hydrology, Hydrogeology and Hydrogeochemistry

The hydrological regime is greatly influenced by climate and regional topography. Since surface hydrology is highly dependent on climate, substantial changes can be anticipated during altered climate domains at other stages of a glacial cycle.

With the limited changes in topography projected over the assessment timeframe, it is reasonable to assume that, under future temperate climate domains, surface water flows will follow a similar pattern to those in the region during the current temperate period. The water balance is unlikely to change dramatically during continuous temperate climate conditions at Forsmark. Future surface water bodies will therefore largely be shallow oligotrophic freshwater lakes, as evident under current biosphere conditions, that will be transformed into mires as the process of terrestrialisation occurs. Topography is of low relief and ice sheets are not envisaged to have a dramatic impact on the future surface topography of the area. Thus, significantly incised river channels are not expected to occur.

In terms of the marine environment, the interplay between glacially induced isostatic depression/recovery and eustatic sea-level variations is of great importance. This interplay gives changing local water depths and residence times as well as a changing regional circulation and alterations in the salinity of water bodies in the Baltic basin. As isostatic recovery continues, the Baltic Sea may become isolated from the Atlantic, which would reduce salinity below current brackish water conditions. The northern area (the Gulf of Bothnia) will be isolated from the rest of the Baltic Sea at around 25,000 years AP as a result of continued isostatic uplift, resulting in the formation of a lake. There will therefore be three distinct stages in terms of marine development. These comprise an open sea stage, an open-ended coastal stage (similar to the present stage) and a bay stage with only one open boundary.

During the open sea stage the water turnover will be rapid and similar in the whole model area and in the open Baltic Sea. Oceanographic conditions will be fairly homogenous and the water exchange is at its maximum. In the open-ended coastal stage a net through-flow of the area is still possible, although the water retention time increases as a result of a complex interplay between a narrower southern boundary, decreasing volumes of the marine basins and decreases in the cross-sectional areas between adjacent basins. The water turnover during this stage is primarily determined by the wind and fluctuating sea levels, and water retention times will be longest in the shallow basins located far from the boundaries to the Baltic Sea. During the bay stage, the southern entrance has closed and Öregrundsgrepen has been transformed into a bay, whereby the water retention time for the whole area increases. The oceanographic conditions will be typical of estuarine circulation in an enclosed bay. The basins gradually become more enclosed and are one by one transformed into lakes. Runoff from land becomes more important for water turnover during this stage.

The groundwater flow is, at the present time, driven to a large degree by topographic gradients in the landscape and, during future periods of temperate climate domain the groundwater flow pattern will be similar to that at present. There will thus be a mixture of local areas of groundwater recharge, typically at topographically high positions, and discharge typically in low positions.

Groundwater in the uppermost 100 to 200 m of bedrock displays a wide range of chemical variability, particularly in terms of chlorine concentrations suggesting both brackish and meteoric influences. The extent of saline influence is likely to diminish with continued shoreline displacement. However, a greater influence would be expected in response to submergence by the brackish waters of the Baltic Sea as the influence of meteoric waters is removed. Should submergence by a freshwater lake occur, reduced salinity in groundwater would be expected.

During the initial periods of periglacial climate domain there is initially sporadic permafrost followed by discontinuous spatial permafrost coverage which results in a modified pattern of groundwater flow, but with significant groundwater recharge and discharge occurring. As climate cools further and continuous permafrost forms, the recharge of groundwater is strongly reduced or even stopped. However, it is unlikely that the permafrost layer will have zero permeability for groundwater flow as this would require a uniform and very deep permafrost distribution.

At locations of future deep lakes, unfrozen through taliks may exist where groundwater recharge and discharge takes place. In the scenario in which the next glacial-interglacial cycle is similar to the last, taliks are initially likely to form at around 26 ka AP. Increased groundwater flow due to the large pressure gradient associated with an advancing ice-sheet margin over permafrost terrain is likely to enhance the creation of taliks.

During the first period of glacial climate domain, the ice sheet overrides ground with permafrost. The subglacial permafrost under the ice-sheet margin acts as a hydrological barrier to groundwater flow and this phase is therefore characterised by a period with no groundwater recharge under the marginal zone of the ice sheet, although recharge is likely to take place far from the margin of the ice sheet where the permafrost will have melted.

For most of the ice-covered time, warm-based ice with free water present at the ice-bed interface is envisaged and it is estimated that Forsmark will be covered by wet-based ice for around 23,000 years in each glacial cycle (around 75% of the ice-covered time). As such, for most of the time when the area is covered by ice sheets, meltwater is present at the ice-sheet bed, typically produced at rates of a few mm/year and hence groundwater recharge by glacial meltwater occurs.

Groundwater recharge will typically occur in local areas of former groundwater discharge under glacial conditions, resulting in a dominant subglacial groundwater flow directed downwards, recharging the groundwater aquifer. Groundwater discharge may occur close to the ice margin, where water flows will be augmented by meltwater from the ablation zone. Indeed, these meltwater flows may be substantially larger than groundwater flows. They may either be from the surface of the ice sheet or may penetrate into fissures in the ice and emerge basally at the ice margin. Should an ice-sheet still-stand occur at the site, hydraulic gradients could be affected to a high degree: it is estimated that there is an approximately 1 km wide zone of high groundwater fluxes both in front of and behind the ice-sheet margin. The increased physical and hydraulic gradient caused by the load of the ice sheet, and particularly close to the ice-sheet margin, is likely to increase groundwater flow in the bedrock compared with temperate climate conditions.

During the second and more severe glacial phase, the ice sheet is cold-based for a considerably shorter initial time than during the first major glacial phase, which makes water from surface and basal melting available for groundwater recharge during most of this period of ice-sheet coverage. As in the case of the first ice-covered period, steeper physical and hydraulic gradients, especially associated with the passage of the ice margin may, for a limited period, induce more rapid and substantial groundwater flow than under present ice-free conditions.

The ice sheet thickness sets a limit to the maximum hydrostatic pressure that may occur at the ice sheet/bed interface. The additional hydrostatic pressure that may occur at Forsmark, based on the glacial maximum, is 26 MPa.

Atmosphere

The air flow regime will be affected over ice sheets.

Narrative for the Future

Based on the narrative above, it is evident that there are three climate domains that can be expected to occur in Sweden in a 100 ka time perspective that are important in terms of repository safety, based on reconstruction of the last glacial cycle. These are:

- Temperate climate domain,
- Periglacial climate domain, and
- Glacial climate domain.

Both periglacial and temperate climate domains may be associated with periods of submergence of the repository location by the Baltic Sea or a freshwater lake. Submerged conditions represent 16% of the total duration of the reference glacial cycle. The variation in climate domain over the reference glacial cycle is presented in Figure B.9.

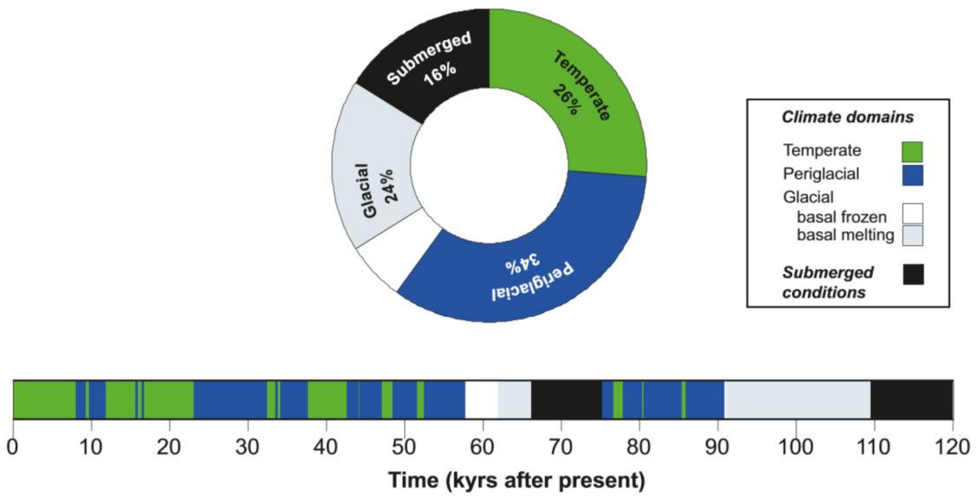


Figure B.9: Duration of Climate Domains and Submerged Conditions at Forsmark in the SR-Site Reference Glacial Cycle, expressed as Percentages of the Total Time.

The bar below the pie chart shows the temporal development of climate-related conditions for the reference glacial cycle as a time series of climate domains and submerged periods (reproduced from Figure 10-106 of SKB [2011].

Although alternative future projections of climate can be developed for Forsmark (e.g. inclusion of an extended inter-glacial episode arising as a consequence of anthropogenic, greenhouse-gas warming) the reference glacial cycle includes the full range of climate and landscape conditions of interest at the site, so it is the only narrative for climate and landscape development that is carried forward in this appendix. A narrative including an extended interglacial episode is developed for Lowland Britain in Section B.3.2.

Approach to Representing Environmental Change

In broad terms, the narrative set out above and encapsulated in Figure B.9 can be considered in terms of the following states.

S1: Temperate climate with the site submerged below coastal waters;
S2: Temperate climate with the site located below a near-coastal terrestrial environment;
S3: Periglacial climate with the site submerged below coastal waters;
S4: Periglacial climate with the site located below a near-coastal terrestrial environment;
S5: Glacial climate with an ice sheet covering the site.

From Figure B.9, relevant transitions between these states can also be identified. These are summarised in Table B.7.

Table B.7: Climate and Landscape Transitions at Forsmark

Transition	Initial State	Final State	Description
T1	S1	S2	Temperate climate throughout, with isostatic recovery leading to a transition from an offshore to a terrestrial context for the site.
T2	S2	S4	Cooling of climate with the development of deep permafrost in a terrestrial context. Transition to tundra-type vegetation.
T4	S4	S2	Warming of climate with the melting of deep permafrost in a terrestrial context resulting in a temperate climatic regime similar to the present day.
T5	S4	S5	Cooling of climate with the ice margin advancing over the site. Transition from a frozen base of the ice sheet to a wet base.
T6	S5	S3	Warming of climate with the ice margin retreating over the site resulting in submerged conditions at the site.
T7	S3	S1	Transition of limited significance, included for completeness to represent the decay of permafrost in post-glacial submerged conditions.

Note that not all potential transitions occur in the reference glacial cycle. For example, S2 to S1 does not occur, because post-glacial isostatic recovery always outpaces eustatic sea-level rise at the site under temperate conditions.

Each state S1 to S5 can be characterised in terms of its principal components (climate, atmosphere, topography, near-surface lithostratigraphy, water bodies and biota). However, following from the discussion above, it is clear that the overall topography is little altered during a glacial-interglacial cycle. Furthermore, there are only minor changes in atmospheric characteristics between the states. Thus, attention can be concentrated on the remaining components. As these are discussed extensively above, only a brief summary is provided in Table B.8.

Table B.8: Summary Characteristics of the Various Landscape States

State	Climate	Near-surface Lithostratigraphy	Water Bodies	Biota
S1	Temperate	Extensive till, mineral sediments of varying textures ranging from clay to sand and gravel, subject to transport by wave action. Some rock outcrops.	Brackish coastal waters	Coastal marine ecosystem including both benthic and pelagic organisms; hard and soft bottoms, some bottoms in the photic and some in the aphotic zones; range of species limited by brackish conditions
S2	Temperate	Extensive till, organic deposits in lake basins and mires. Some rock outcrops.	Oligotrophic lakes, wetlands, minor streams; groundwater within about 1 m of the ground surface	Forest dominated landscape, but with lakes and mires; cultivated land also present
S3	Periglacial	Extensive till, mineral sediments of varying textures ranging from clay to sand and gravel, subject to transport by wave action. Some rock outcrops.	Brackish coastal waters	Coastal marine ecosystem including both benthic and pelagic organisms; hard and soft bottoms, some bottoms in the photic and some in the aphotic zones; range of species limited by brackish conditions
S4	Periglacial	Extensive till, organic deposits in lake basins and mires. Some rock outcrops.	Freshwater lakes and wetlands; active layer with high moisture content in summer; perennially frozen ground at depth	Tundra-type vegetation and corresponding fauna
S5	Glacial	Limited unconsolidated sediments beneath ice sheet.	Warm-based ice-sheet with an active hydrological regime at its base	Very limited biotic utilisation of the ice sheet

Following the approach adopted by SKB in SR-Site [SKB, 2011], it seems likely that the GBI can be fully characterised in the context of these states and transitions. Here, attention is focused on state S2. In Section B.3.2, a sequence of states is considered in the context of Lowland Britain. However, the issue of developing conceptual models for transitions is not addressed in this appendix. This is a matter for consideration in any future programme of work.

Interaction Matrices for the Geosphere-biosphere Sub-system

The main components of State S2 can be shown on an interaction matrix. This is shown in Figure B.10. Similar interaction matrices can be developed for the other states, but these are not illustrated.

Temperate climate	Determines seasonal temperatures and precipitation.	No incision occurs.	Acts as control on rates of organic matter generation and degradation.	Precipiation can influence fracture mineral amounts and composition in the long term.	Defines water availability and hence flow regime.	Maintains water table in sediments.	Source of recharge to fracture systems.	Limits range of crops that can be grown and determines irrigation requirements.
No significant influence.	**Low to moderate levels of atmospheric pollution. Generally low dust loads.**	No significant influence.	No significant influence.	No significant influence.	Minor influence on water chemistry.	Minor influence on water chemistry.	Minor influence on water chemistry.	No significant influence.
No significant influence.	No significant influence.	**Subdued topography. Depressions in the bedrock infilled by thicker layers of unconsolidated sediment. Little incision into the bedrock surface.**	Control on thickness of sediments and locations of lakes.	No significant influence.	Controls the geometry of the surface flow regime.	Water table height is controlled by topographic variations, resulting in local flow cells in the near-surface environment.	Water table height is controlled by topographic variations, resulting in local flow cells in the near-surface environment.	No significant influence.
No significant influence.	No significant influence.	Develops to infill lows in topography.	**Mainly till. Organic sediments in lake basins and mires. Some outcrops of the underlying rock.**	No significant influence.	Structure and development modifies the surface flow regime.	Controls chemistry of groundwater.	Controls chemistry of groundwater. Structure of deposits influences recharge to fractures and discharge from fractures.	Organic sediments when drained may be used for agriculture. Rocks and boulders in till limit the use of land for agriculture.
No significant influence.	No significant influence.	Fundamental control on topography. Strongly resistant to erosion, but sub-vertical fracture systems can be associated with bedrock lows.	No significant influence.	**Ancient fractured hard rock. Includes both sub-vertical and sub-horizontal fracture sets in the near surface.**	Fractures control recharge from and discharge to the surface water system.	Fractures control recharge from and discharge to superficial sediments.	Rock type and fracture minerals affect water chemistry. Size and connectivity of fractures determine the groundwater flow regime.	No significant influence.
No significant influence.	No significant influence.	No significant influence.	Surface flow regime acts as a control on rates and amounts of organic matter production.	No significant influence.	**Oligotrophic lakesand mires connected by stream channels eventually discharging to the marine environment.**	Exchange between surface waters and waters in superficial deposits.	Fractures may be recharged directly from lakes and mires.	Contol on land use.
No significant influence.	No significant influence.	No significant influence.	Control on organic matter production and degradation.	No significant influence.	Exchange between surface waters and waters in superficial deposits.	**Limited groundwater in the superficial sediments.**	Exchange between groundwater in superficial sediments and fracture water in the bedrock.	Contol on land use.
No significant influence.	No significant influence.	No significant influence.	No significant influence.	Control on fracture mineral formation or dissolution.	Fractures can discharge directly to lakes and mires.	Exchange between groundwater in superficial sediments and fracture water in the bedrock.	**Water present mainly in fracture systems in the underlying rock**	Available for irrigation.
Minor influence through differential evapotranspiration from different plant types.	No significant influence.	No significant influence.	Agricultural reclamation of mires.	No significant influence.	Agricultural reclamation of mires, including control of surface drainage.	Influenced by land use, including both irrigation and well drawdown.	Abstraction of water perturbs the flow system and may result in the introduction of oxygen into the fracture system.	**Mainly forested landscape, but mires present and some areas of agricultural land.**

Figure B.10: Interaction Matrix for State S1 at Forsmark

In Figure B.10, the shaded cells indicate interactions that are likely to be of significance. These are relevant to the following analysis. Overall, the climate and the subdued topography control the development of organic sediments. However, the control of the development of those sediments is also affected by the surface water and groundwater flow and hydrochemical regimes, and, in turn, the characteristics of those sediments influence the flow regimes. The structure of the till and the nature of the organic sediments influence the areas where agriculture is practiced. In turn, agriculture influences the structure of these deposits, e.g. by enhancing the degradation of organic matter.

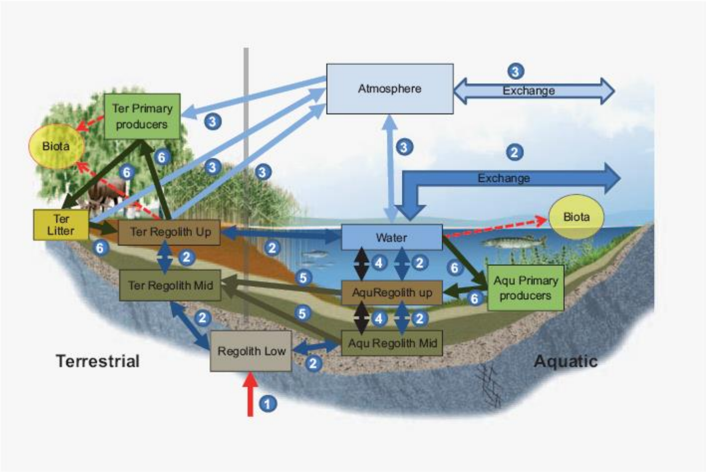
Characterisation of the Geosphere-biosphere Sub-system in a 3D Model

Climate

The climatic conditions appropriate to State S2 have already been described, since they are those applicable at the present day. Forsmark is located in Southern Sweden, which has a Cfb climate according to the Köppen-Trewartha (or Köppen-Geiger) classification; it is a warm temperate humid climate with the warmest month on average being lower than 22°C and an average of four or more months above 10°C. The mean annual air temperature at Forsmark itself is approximately 7°C and the vegetation period, at which the air temperature remains above 5°C, lasts approximately from May to September. The region shows a strong precipitation gradient in the east-west direction. The annual precipitation in the Forsmark area is about 546 mm a^{-1}, which is lower than the 30 year long-term mean precipitation of 690 mm a^{-1} at 15 km west of the Forsmark area, but higher than the 490 mm a^{-1} at a similar distance north-east of Forsmark. On average, snow covers the ground for 105 and 80 days per season on forest land and open land, respectively, and the period of snow cover is typically from the end of November until the beginning of April. The maximum snow depth recorded at the site is 48 cm in forest land and 25 cm in open land, and the maximum snow water content is 144 and 64 mm, respectively. Measurements of ground frost penetration during three seasons (2003/04–2005/06) showed that ground frost was present for 40 and 80 days/season in forest land and open land, respectively. The maximum ground frost depth was 0.46 m on open land, and only 0.08 m on forest land.

Topography and Lithostratigraphy

To a large degree, the appropriate topographic and lithostratigraphic structure for a 3D model has already been addressed by SKB [2011]. The overall geometrical arrangement appropriate to State S2 is well illustrated by the cross-section shown in Figure A.11. However, within this broad framework individual components need to be considered. This is illustrated for a lake and the associated terrestrial environment in Figure B.11.



Model name	Description
Regolith Low	The lower part of the regolith overlying the bedrock, primarily composed of till. It is common to the terrestrial and aquatic parts and its origin is from the glaciation.
Aqu Regolith Mid	The middle part of the regolith in the aquatic part of biosphere objects, usually consisting of glacial and postglacial clays, gyttja and finer sediments which originate mainly from the period after the retreat of the glacial ice sheet, or from later resuspended matter mixed with organic sediments.
Aqu Regolith Up	The part of the aquatic regolith with highest biological activity, comprising c. 5–10 cm of the upper aquatic sediments where resuspension and bioturbation can maintain an oxidising environment.
Ter Regolith Mid	The middle part of the terrestrial regolith, containing glacial and postglacial fine material, i.e. former sediments from the seabed / lake bottoms.
Ter Regolith Up	The upper part of the terrestrial regolith which has the highest biological activity, like the peat in a mire, or the plowing layer in agricultural land.
Litter	Dead plant material overlying the regolith.
Water	The surface water (stream, lake, or sea water).
Aqu Primary Producers	The biotic community in aquatic habitats, comprising both primary producers and consumers.
Ter Primary Producers	Terrestrial primary producers.
Atmosphere	The lower part of the atmosphere where released radionuclides are fully mixed.

Figure B.11: Conceptual Illustration of the Radionuclide Model for a Biosphere Object. Boxes represent compartments, thick arrows fluxes, and dotted arrows concentration computations for non-human biota (these are not included in the mass balance). The model represents one object which contains an aquatic (right) and a terrestrial part (left) with a common lower regolith and atmosphere.The source flux (1 Bq/y) is represented by a red arrow (1). The radionuclide transport is mediated by different major processes, indicated with dark blue arrows for water (2), light blue for gas (3), black for sedimentation/resuspension (4), dark brown for terrestrialisation (5), and green for biological uptake/decomposition (6). Import from and export to surrounding objects in the landscape is represented by arrows marked "exchange". Brief descriptions of the compartments are given in the table below the figure. Based on Figure 13-6 and Table 13-1 of SKB [2011].

For the purpose of considering the GBI, it is appropriate to simplify the structure shown in Figures A.11 and B.11. This simplified conceptual structure is illustrated in Figure B.12.

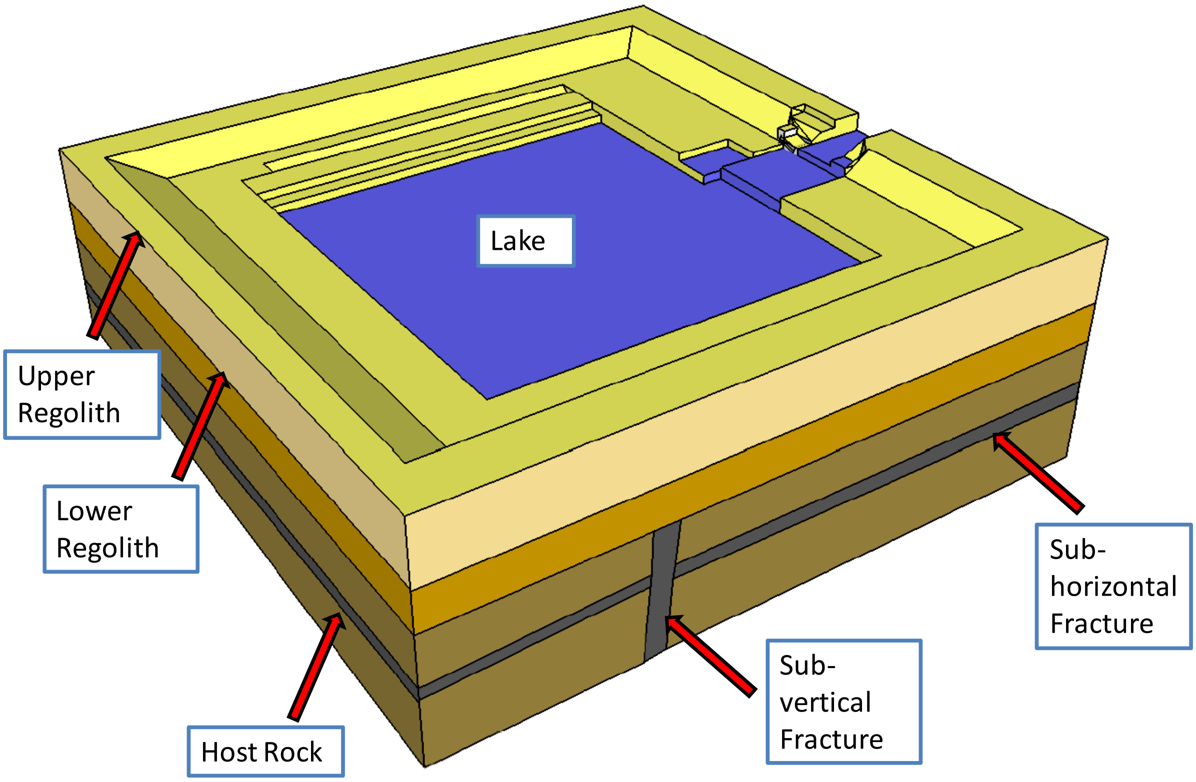


Figure B.12: Simplified Conceptual Structure of a Lake

An illustrative cross section showing the sub-vertical fracture is shown, more realistically, in Figure B.13.

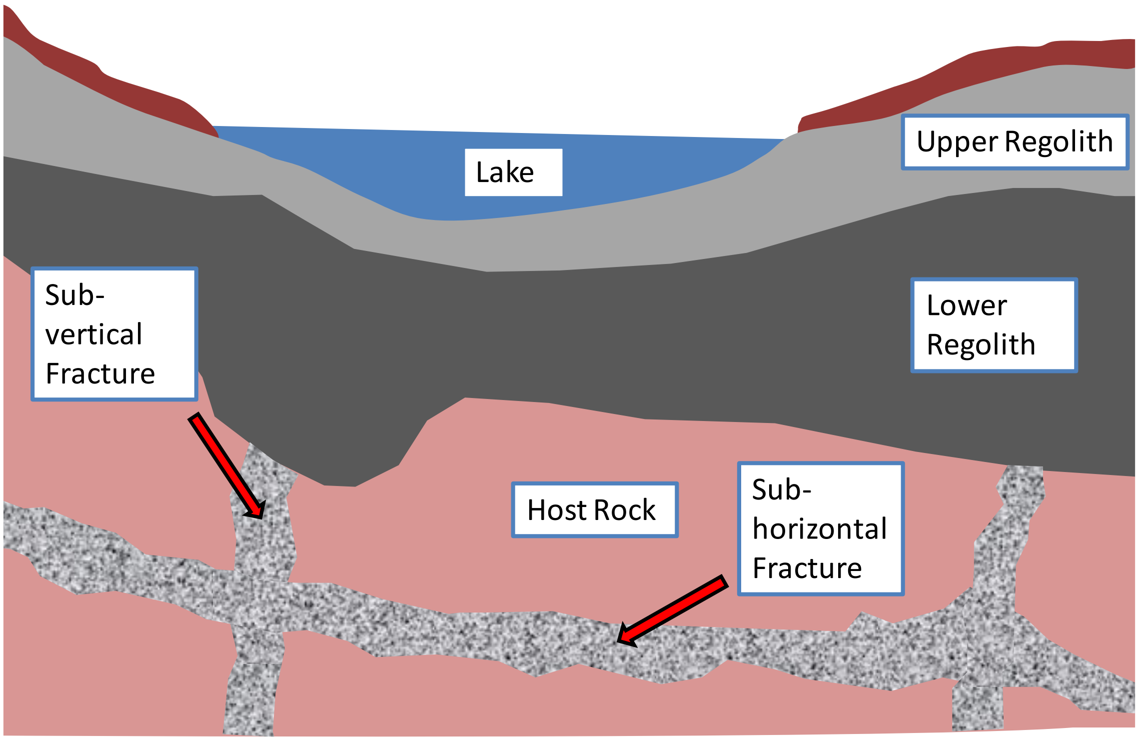


Figure B.13: Illustrative Cross-section of the Representative Geosphere-biosphere Subsystem

As discussed above, the major part of the landscape is covered by a thin regolith layer with a mean depth in the Forsmark area of c. 4 m. Exposed bedrock and bedrock with only a thin regolith layer (<0.5 m) occupy c. 9% of the area. The major portion of regolith at Forsmark is glacial deposits, reworked during multiple glaciations and relocated by subsequent glacial and post-glacial processes. The upper part of the regolith is affected by deposition and decomposition of organic material, and in terrestrial areas also by weathering of the original material, thus forming soil in terrestrial areas and sediments, often rich in organic matter, in aquatic areas.

Approximately 90% of the ground surface in the Forsmark area consists of regolith that originates from the last glaciation when the ice sheet reworked and redistributed sediments of earlier Quaternary glaciations. The distribution of regolith is typical of areas in Sweden below the highest postglacial coastline. Elevated parts of the terrain are dominated by till or exposed bedrock and valleys have a higher percentage of clay and post-glacially re-deposited fine-grained material. Till constitutes the dominant regolith exposed at the ground surface, occupying approximately 65% of the terrestrial surface areas and 30% of the area currently submerged by the sea. Generally, the till is thicker in depressions, thus levelling out some of the bedrock relief. The till in the Forsmark area is subdivided into:

1) a sandy till with medium frequency of superficial boulders (dominant),
2) a clayey till with low boulder frequency, and
3) a sandy till with high boulder frequency.

Clay, gyttja clay, sand and peat occur frequently, but in scattered deposits, mainly covering smaller patches. Peat accumulation occurs in all Forsmark wetlands, but deposits thicker than 0.5 m are restricted to the south-western part of the area. This is the most elevated part of the Forsmark area and has, therefore, experienced terrestrial conditions and peat accumulation for the longest time.

In the context of Figure B.13, it is reasonable to consider the lower regolith to be a sandy till containing boulders, the upper regolith to be a more clayey till with low boulder frequency. Overlying these are terrestrial soils and aquatic sediments with high organic matter content.

Surface Water and Groundwater Flow Regime

As the GBI is primarily of interest where radionuclides are discharged into the near-surface environment, upward flow in the sub-vertical fracture system is envisaged. Flow in the sub-horizontal system will primarily be down the topographic slope. When upward moving waters from the fracture system enter the lower regolith till, they will be diverted laterally, as a consequence of their meeting with infiltrating meteoric waters, which will also be diverted laterally. The upper regolith is likely to be of lower hydraulic conductivity than the lower regolith, further encouraging lateral diversion of upwelling groundwater. Notwithstanding its finer texture than the lower regolith, most precipitation will infiltrate through the upper regolith. Beneath lakes, organic sediments may preferentially impede the upward transport of water, forcing discharges to occur at their margins or beyond. Although much of the precipitation entering catchment soils will infiltrate, some will be transferred to the lake by surface runoff and some by interflow at the boundary between the soil and the underlying, fine-grained upper regolith. The water content of the lake will be replenished by recharge from its catchment, by channel flow, if there are channels feeding into the lake from upstream (not shown in Figure B.12), and by direct precipitation onto its surface. Losses from the lake will be via stream channels, evaporation and water extraction (if practiced). The general surface water and groundwater flow regime is illustrated in Figure B.14.

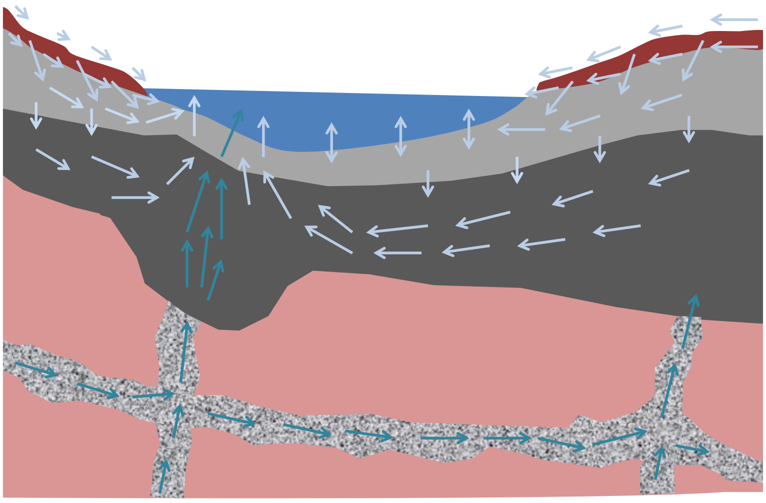


Figure B.14: Schematic Groundwater and Surface Water Flow Regime

Meteoric water and fracture water are distinguished by lighter and darker arrows respectively. An alternative flow regime is illustrated in Figure B.15. In this case, the sediments of the lake bed exhibit a reduced hydraulic transmissivity and the upwelling groundwater flow is directed towards the margins of the lake.

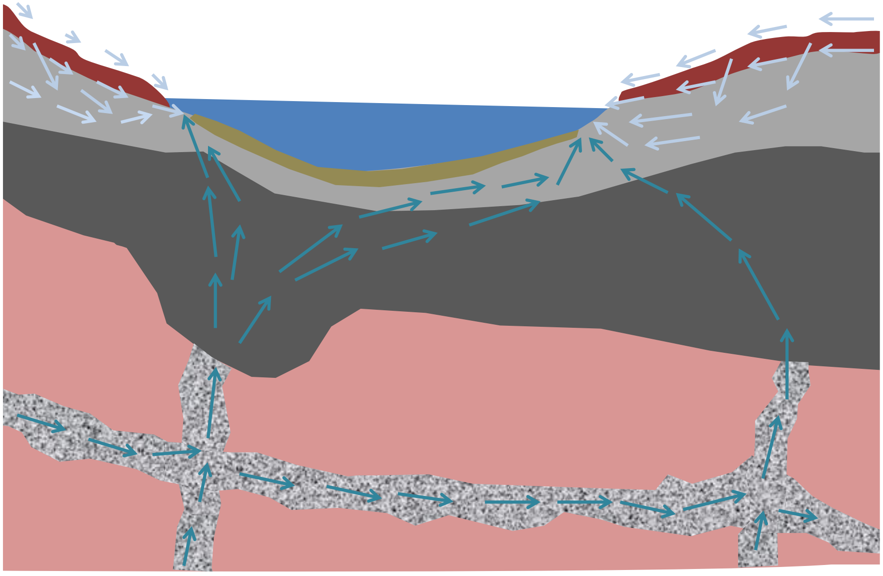


Figure B.15: Flow Diversion beneath a Lake

Hydrochemistry

As illustrated in Figures B.14 and B.15, the two main water types in the GBI are recent meteoric water entering as precipitation and fracture water. There is little ambiguity over the chemical composition of the recent meteoric water. Furthermore, State S2 corresponds closely to the present situation. Observationally, it is found that since the emergence of Forsmark from the Baltic Sea, the pre-existing Littorina and Last deglaciation groundwater has been forced downward by recent meteoric water. This means that the fracture water in the near-surface interconnected fracture system is likely also to be recent meteoric water, though it will be modified to a limited degree by rock-water interactions. Probably the main distinction is that the water in the most superficial deposits will be oxic, whereas the water at greater depths, including that in fractures, will be anoxic.

Thermal Regime

The near-surface fracture system extends down to a few tens of metres. Thus, heat from a deep KBS-3 repository will have little impact upon it. In State S2, the mean annual air temperature will be about 7^{o}C, so there will be no permafrost development and ground temperatures below about 2 m depth will remain above freezing throughout the year. Observations indicate that in winter ground freezing may extend from the surface down to, at most, about 0.5 m.

Perturbations due to Human Actions

The main potential for perturbation of the GBI is through the construction of wells. These could be dug wells in the superficial strata or boreholes into the bedrock. The latter are of greater interest, as they have the potential to intersect the fracture system, bring undiluted fracture waters directly to the surface, where they could be used for domestic purposes and agricultural irrigation. Such boreholes would typically be cased in the superficial strata, so that almost all the abstracted water would originate from the fracture system in the bedrock.

The pumping rate for this well might be as low as a fraction of a cubic metre per day for a domestic well up to a few hundred cubic metres per day with the abstracted water used for commercial agricultural purposes (see also Appendix A, Section A.8.1). However, the upper limit on the yield would be constrained by the sustainable flow in the near-surface fracture system.

Spatial and Temporal Flux of Radionuclides

From Figures B.14 and B.15, it is clear that radionuclide fluxes will enter the GBI along one, or at most a few, sub-vertical fractures. Thus, entry locations may be approximated by linear features at the base of a 3D model. However, in practice, transport of radionuclides through the geosphere has typically been represented using 1D flow pathways and discharge locations have been estimated using particle tracking from individual waste container locations. This modelling approach provides no information on the spatial distribution of radionuclide flux and yields discharge points (though the tracking of multiple particles from a single waste container location can give information on the spatial distribution of discharge points). Hence, it may be appropriate to consider that radionuclides enter the GBI either at a single point location or with their fluxes uniformly distributed along a pre-defined extent of a linear feature. The distinction is probably not very large in assessment terms, as transport in the near-surface fracture system and overlying regolith will tend to spatially disperse radionuclides.

Outputs Required

SKB estimates time-dependent Landscape Dose Factors. Thus, the outputs required are time-dependent concentrations of radionuclides in the various components of a set of inter-linked biosphere objects. These concentrations can then be used to determine external exposures of and intakes of radionuclides by humans making maximal reasonable use of local, contaminated resources.

Processes Operating within the Model and their Significance

Based on the discussion above, the following distinct components of the GBI are identified (note that agricultural land is not included in this simplified example and it is also assumed that bedrock does not outcrop at the surface within the area of interest).

a) Physical components
- a1) Lake bed sediments
- a2) Sediments in mires
- a3) Upper regolith
- a4) Lower regolith
- a5) Bulk host rock
- a6) Fracture systems (in the host rock)

b) Water bodies
- b1) Lake and stream water
- b2) Water in mires
- b3) Groundwater in the upper regolith
- b4) Groundwater in the lower regolith
- b5) Groundwater in the bulk host rock
- b6) Groundwater in fractures

c) Water types
- c1) Meteoric water
- c2) Fracture water
- c3) Mixed water

Water bodies are defined to include both the flow characteristics and composition of those bodies. The composition is determined by mixing of the different water types together with water-rock (or, more generally, water-solid) interactions with the physical components. Thus, there is a degree of overlap in the definitions of water bodies and water types. However, separating the two allows a natural distinction between aspects that are primarily addressed in hydrogeological studies from those addressed in hydrogeochemical studies.

Processes identified as operating between these components are illustrated in Figure B.16.

Lake bed sediments						1,7		1,9						1,15
	Sediments in mires					2,7	2,8	2,9						2,15
		Upper regolith				3,7	3,8	3,9	3,10					3,15
			Lower regolith					4,9	4,10	4,11	4,12			4,15
				Bulk host rock					5,10	5,11	5,12		5,14	5,15
					Fracture systems				6,10	6,11	6,12		6,14	6,15
7,1		7,3				**Lake and stream water**	7,8	7,9						7,15
	8,2	8,3				8,7	**Water in mires**	8,9						8,15
9,1	9,2	9,3	9,4			9,7	9,8	**Groundwater in upper regolith**	9,10					9,15
		10,3	10,4	10,5	10,6			10,9	**Groundwater in lower regolith**	10,11	10,12			10,15
			11,4	11,5	11,6				11,10	**Groundwater in bulk host rock**	11,12			11,15
			12,4	12,5	12,6				12,10	12,11	**Groundwater in fractures**		12,14	12,15
	13,2	13,3				13,7	13,8	13,9				**Meteoric water**		13,15
										14,11	14,12		**Fracture water**	14,15
15,1	15,2	15,3	15,4	15,5	15,6	15,7	15,8	15,9	15,10	15,11	15,12			**Mixed water**

Figure B.16: Interaction Matrix for Components of the Geosphere-Biosphere Sub-system in State S2

Some comments on the interaction matrix shown in Figure B.16 are required. First, the major components of the system are shown on the lead diagonal. Solids are coloured reddish-brown, water bodies blue and the chemical compositions of waters are shown in red. The geometry is that of Figures B.14 and B.15, so components that are not in direct contact do not affect each other. Here and throughout this discussion text in bold refers to the lead diagonal elements in Figure B.16.

As the state is considered to be time-independent in this illustration, the solid components do not interact directly with each other. However, interactions do occur indirectly through the included waters. Solids condition their included waters (e.g. **Upper regolith** conditions **Groundwater in upper regolith** through element 3,9) and included waters affect the associated solid (e.g. **Groundwater in upper regolith** conditions **Upper regolith** through 9,3). There are also interactions at the interfaces between one solid and another, e.g. **Groundwater in fractures** encounters the **Lower regolith** at such a boundary and affects it through 12,4. The various included waters can flow across the boundaries between different media, carrying radionuclides and affecting the composition of the included waters, e.g. **Lake and stream water** can recharge **Groundwater in upper regolith** (7,9) and **Groundwater in fractures** can discharge into **Groundwater in lower regolith** (12,10).

A key role of **Meteoric water** and **Fracture water** is the formation of **Mixed water** (13,15 and 14,15). However, the composition of **Mixed water** is altered throughout the system by direct interactions with solids (1,15; 2,15; 3,15; 4,15; 5,15; 6;15) and by interactions with the fluids included in those solids (7,15; 8,15; 9,15; 10,15; 11,15; 12,15). This implies a complete set of reverse reactions (15,1 through 15,12).

The end member **Fracture water** is shown as influencing, and being influenced by **Groundwater in fractures** (14,12 and 12,14). This is to emphasise that it may not be possible to define the true end-member water that is uninfluenced by fracture characteristics.

In general terms, interactions at interfaces are likely to be of much less significance than flows across them or interactions within the bulk of components. This leads to the simplification of Figure B.16 in Figure B.17, where interactions of minor significance have been greyed out. Note that interactions between fractures and the host rock are treated as an exception to this rule owing to the intimate association between these two components.

Lake bed sediments						1,7		1,9						1,15
	Sediments in mires					2,7	2,8	2,9						2,15
		Upper regolith				3,7	3,8	3,9	3,10					3,15
			Lower regolith					4,9	4,10	4,11	4,12			4,15
				Bulk host rock					5,10	5,11	5,12		5,14	5,15
					Fracture systems				6,10	6,11	6,12		6,14	6,15
7,1		7,3				**Lake and stream water**	7,8	7,9						7,15
	8,2	8,3				8,7	**Water in mires**	8,9						8,15
9,1	9,2	9,3	9,4			9,7	9,8	**Groundwater in upper regolith**	9,10					9,15
		10,3	10,4	10,5	10,6			10,9	**Groundwater in lower regolith**	10,11	10,12			10,15
			11,4	11,5	11,6				11,10	**Groundwater in bulk host rock**	11,12			11,15
			12,4	12,5	12,6				12,10	12,11	**Groundwater in fractures**		12,14	12,15
	13,2	13,3				13,7	13,8	13,9				**Meteoric water**		13,15
										14,11	14,12		**Fracture water**	14,15
15,1	15,2	15,3	15,4	15,5	15,6	15,7	15,8	15,9	15,10	15,11	15,12			**Mixed water**

Figure B.17: Principal Interactions for Components of the Geosphere-Biosphere Sub-system in State S2

When perturbations by wells are included, the above system has to be extended to include the well as a physical component and abstracted well water as a water body. This matter is not considered further here, as it is addressed in some detail in the Lowland Britain example discussed in Section B.3.2.

Coupling between Components

Coupling between components is evaluated for the principal components shown in Figure B.17. These couplings can be distinguished into a limited number of categories. This is illustrated in Table B.9, which also sets out the processes that would result in these couplings.

Table B.9: Processes determining the Couplings shown in Figure B.17.

Interactions (Numbered as in Figure 4.11)	**Description of the Interactions**	**Relevant Processes**
1,7; 2,8; 3,9; 4,10; 5,11; 6,12; 7,1; 8,2; 9,3; 10,4; 11,5; 12,6	Interactions between a solid and its included water	Sorption/desorption; precipitation/dissolution; colloid formation and dissolution; advective and dispersive transport within the solid, including diffusion into intra-particle and inter-particle pore spaces. Relevant both to the composition of the solid and its included water and to the transport of contaminants within the solid/water system.
1,15; 2,15; 3,15; 4,15; 5,15; 6,15	Effects of a solid on the composition of waters formed by the mixing of meteoric and fracture waters	Rock-water interactions that modify the chemical composition of waters with different degrees of mixing. Mainly relevant to defining the composition of waters within which contaminant transport occurs.
5,14; 6,14; 12,14; 14,12; 14,11	Interactions between the host rock and fractures influencing the composition of the 'effective end member' **Fracture water** in relation to the variable composition of **Groundwater in fractures**	Rock water interactions.
7,8; 8,7	Exchange of surface water between lakes and streams and mires	Mainly relevant to contaminant transport.
7,9; 9,7	Exchange of water between lakes and streams and the upper regolith	Recharge and discharge through the lake and stream banks and bed. Mainly relevant to contaminant transport.
8,9; 9,8	Exchange of water between mires and the upper regolith	Recharge and discharge through the base of the mire. Mainly relevant to contaminant transport.
9,10; 10,9; 10,11; 10,12; 11,10; 11,12; 12,10; 12,11	Flows of groundwater across interfaces from one medium to another	Advective flow of water in both unsaturated and saturated conditions. Relevant to bringing different waters into contact for mixing processes and for the transport of contaminants.

Table B.9: Processes determining the Couplings shown in Figure B.17 (Continued)

Interactions (Numbered as in Figure 4.11)	Description of the Interactions	Relevant Processes
7,15; 8,15; 9,15; 10,15; 11,15; 12,15; 13,15; 14,15;	Production of mixed water as a blending of two end member waters and pre-existing mixed waters in various media	Includes the mixing process and chemical reactions in solution
13,2; 13,3	Direct effect of incoming meteoric water on the characteristics of solids exposed at the surface	Chemical reactions leading to weathering of the solids with changes in composition and structure.
13,7; 13,8; 13,9	Input of meteoric water directly into various water bodies	Mixing and reactions in solution. Groundwater in the upper regolith is included because some areas will be exposed in the lake and stream catchment.
15,1; 15,2; 15,3; 15,4; 15,5; 15,6	Chemical interactions of mixed waters with environmental solids	Sorption/desorption; precipitation/dissolution; colloid formation and dissolution
15,7; 15,8; 15,9; 15,10; 15,11; 15,12	Effects of mixed waters of various compositions on the composition of surface waters and groundwaters	Chemical reactions between waters of differing composition leading to changes in chemical speciation and the formation/dissolution of colloids. Mainly relevant to defining the composition of waters within which transport occurs.

B.3.2 Lowland Britain

Assessment Context and Components of the Geosphere-biosphere Sub-system

The assessment context is set out in Table B.10.

Table B.10: Summary of the Assessment Context

Aspect of the Assessment Context	Summary of the Characteristics of this Aspect of the Assessment Context
Purpose of the assessment	Generic assessment intended to demonstrate that a geological disposal facility can be constructed and achieve satisfactory post-closure performance in a range of different geological contexts.
Endpoints of the assessment	Primarily radiological impacts on an individual representative of those more highly exposed in the population {the representative member of a Potential Exposure Group (PEG)}. However, the radionuclide concentrations in environmental media calculated for this purpose may also be used for assessing radiological impacts on non-human biota.
Assessment philosophy	Cautiously realistic, i.e. where there are significant uncertainties cautious assumptions are made, but an attempt is made to avoid the excessive caution that arises from combining several different sets of cautious assumptions, i.e. the overall assessment should be a cautious, but realistic evaluation of how the system is expected to perform.
Repository system	Geological disposal facility at some hundreds of metres depth accommodating both intermediate-level and high-level waste, but with the panels in which the waste types are disposed separated from each other by some distance.
Site context	An inland site in Lowland Britain with the host rock comprising either hard rock or softer sedimentary rock. Evaporites are not available in this context, so are not included in the assessment.
Source term	Spatially distributed plume of radionuclides entering Quaternary sediments from the underlying weathered host rock.
Time frames for assessment	Quantitative assessment required out to 1 10^6 years after closure, but with a greater emphasis on complementary considerations after about 1 10^5 years. Here attention is focused on the first 2 10^5 years after closure, for which detailed landform projections have been made.
Societal assumptions	Technology and societal characteristics are similar to those of the present day, but the society is adapted to the prevailing climate conditions by reference to analogous locations and communities existing at the present day.

Whereas several of the above aspects of the assessment context are self-explanatory, others require further discussion, as provided below.

In respect of the repository system, the overall concept is well illustrated in Figure B.18.

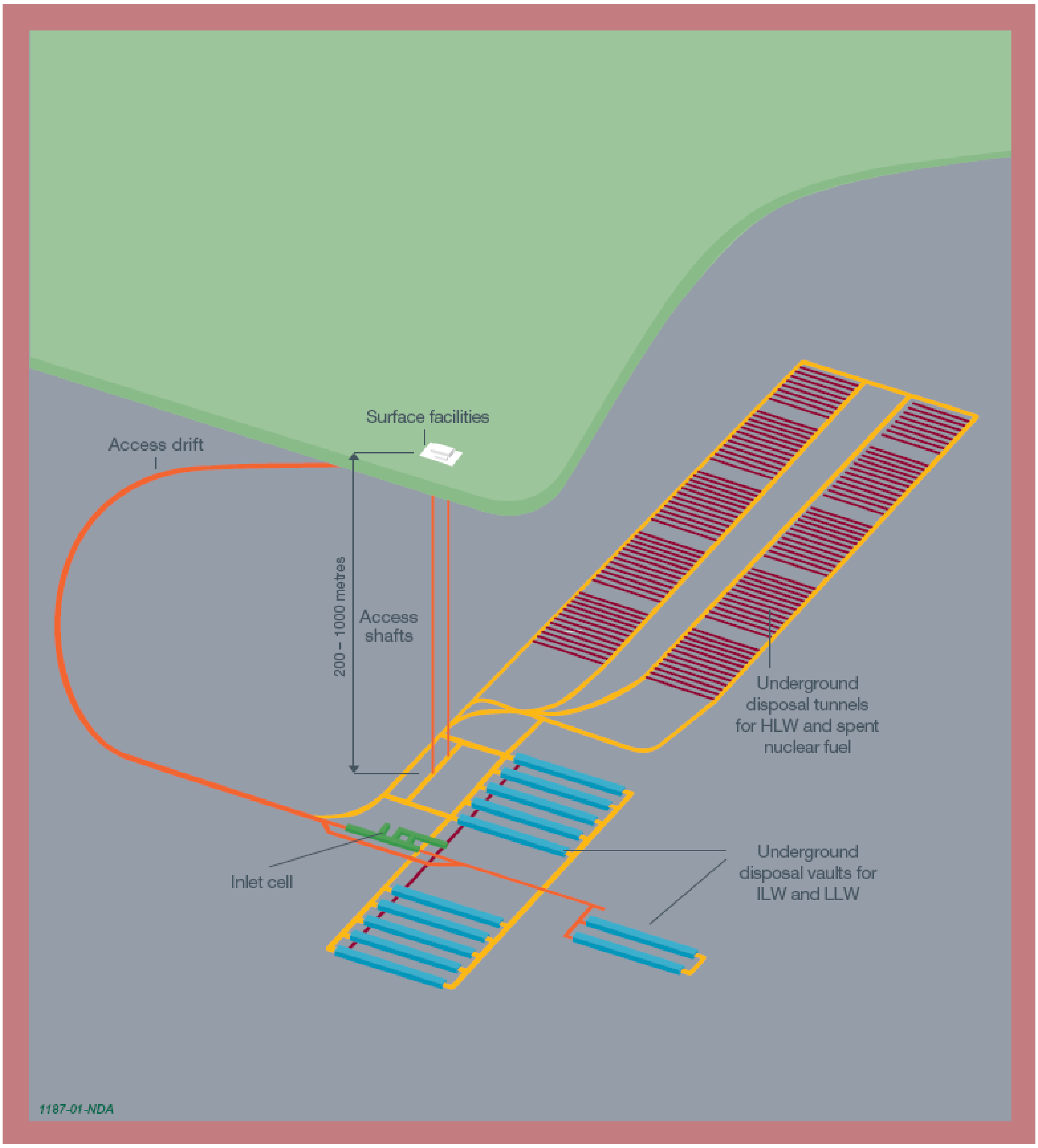


Figure B.18: Schematic Illustration of a Geological Disposal Facility illustrating its General Features [from NDA, 2010a]

As discussed in Appendix A, in the UK at the current stage of the Managing Radioactive Waste Safely (MRWS) process, no site-specific studies are being undertaken. Thus, only generic alternative geological contexts are being modelled in assessment studies. The host rock descriptions used by the

Radioactive Waste Management Directorate (RWMD) of the Nuclear Decommissioning Authority (NDA) correspond to three distinct general rock types that are considered potentially suitable to host a disposal facility for higher activity wastes, based on studies carried out in the UK and internationally, and which occur in the UK. They are described as follows:

- Higher strength rocks - these would typically comprise crystalline igneous, metamorphic rocks or geologically older sedimentary rocks, where any fluid movement is predominantly through divisions in the rock, often referred to as discontinuities. Granite is a good example of a rock that would fall in this category.
- Lower strength sedimentary rocks - these would typically comprise geologically younger sedimentary rocks where any fluid movement is predominantly through the rock mass itself. Many types of clay are good examples of this category of rocks.
- Evaporites - these would typically comprise anhydrite (anhydrous calcium sulphate), halite (rock salt) or other evaporites that result from the evaporation of water from water bodies containing dissolved salts.

However, evaporites of sufficient thickness and extent are not currently identified as being present in Lowland Britain (defined below), so attention is here concentrated on higher strength rocks and lower strength sedimentary rocks, as defined above.

In respect of the site context, it is emphasised that the RWMD has not restricted its search for suitable disposal locations to Lowland Britain. However, this restriction has been imposed within the scope of the present study so as to limit the range of geological and landscape contexts that need to be considered when developing the illustrative examples to which the methodology is applied. Similarly, the scope has been limited to inland sites to avoid the additional complications that arise when addressing landscape changes that occur under the influence of coastal processes. However, this does not eliminate the effects of sea-level changes, since these are propagated to inland sites through alterations in the base level to which rivers grade.

Lowland Britain is defined by Stamp [1946], who cites Sir Halford MacKinder as the source of a simple, yet fundamental, distinction between two roughly equal halves of the island of Britain. If one draws a line approximately from the mouth of the Tees to the mouth of the Exe, it will be found that all the main hill masses and mountains lie to the north and west, the major stretches of plain and lowland to the south and east. This latter area is what is known as Lowland Britain.

Lowland Britain is best described as an undulating lowland, where lines of low hills are separated by broad open valleys and where ‘islands’ of upland break the monotony of the more level areas. Even the highest of the hills scarcely ever exceed 300 m above sea level, though many of the ridges reach about 200 m. The soils tend to be rich and deep, there are few steep slopes to interrupt cultivation and plough lands are to be found right to the tops of the hills. Human settlement is essentially continuous. Villages and towns are closely and evenly scattered. Most land is cultivated or improved, and includes both plough land and grassland. Such unimproved lands as do occur comprise ‘islands’ interrupting the otherwise continuous farmland and coinciding with patches of poorer soils (Stamp, 1946).

This description of Lowland Britain conforms closely to the description of Central England adopted in BIOCLIM [2004]. In that case, the term Central England was employed because the climate was downscaled to the area characterised by the long Central England climate record. However, for all practical purposes, Central England can be regarded as co-extensive with Lowland Britain.

At the present day, the climate of Central England is temperate oceanic (Köppen-Trewartha Class DO). The near-surface lithostratigraphy comprises geometrically complex unconsolidated Quaternary deposits overlying mainly the Liassic clays, Oolite sequence, lower Cretaceous rocks and Chalk. The topography is undulating lowland intersected by fluvially incised river valleys. Generalised erosion and incision of the valleys is now thought to be proceeding only very slowly.

Surface water bodies are mainly flowing rivers and streams. Substantial lakes and wetlands are uncommon, but do occur. In respect of biota, the overall characteristics are those of an intensively farmed environment. Cereal crops, root crops and green vegetables are grown. Fruit growing is practiced extensively, with different areas specialising in soft fruits and tree fruits. In the lower areas, arable land extends over the ridges, as well as occurring in valley bottoms. Grasslands are more common on the higher ridges of the chalk downlands, but, even there, arable agricultural activities can be observed. Sheep grazing is characteristic of these higher areas, but the rearing of cattle for milk and meat is more characteristic of the lowland pastures. Small herds of goats are kept. However, most goats are kept in small numbers domestically. Pigs are reared commercially and domestic fowl are reared both commercially and domestically [BIOCLIM, 2004].

In rural areas, hamlets and villages are the characteristic human communities, with inter-settlement distances of a few kilometres. These hamlets and villages relate economically to market towns (separated by distances ~ 20 km), which in turn relate economically to larger towns and cities. The characteristic small-scale demographic unit is the rural parish. This will typically cover the land area associated with a village and surrounding smaller settlements. Rural parish populations are typically a few hundred to a few thousand individuals. Today, only a small percentage of the inhabitants of a rural parish will be involved in agricultural activities. In general, consumption of locally derived foods is limited, as much of the agriculture is of a large-scale commercial nature. However, vegetable gardening is common, farm shops are popular and pick-your-own fruit options are offered by some farmers. Coarse fishing is a common recreational activity, but very little freshwater fish is caught for human consumption [BIOCLIM, 2004].

The assessment context does not pre-define the GBI, nor does it require that sub-system to be time-independent. Furthermore, it indicates that the range of climatic conditions of relevance to be those likely to occur over the next 2 10^5 years. These considerations have to be kept in mind when identifying and justifying the components of the GBI. The relevant components are identified and justified in relation to the specific assessment context in Table B.11.

Table B.11: Geosphere-biosphere Sub-system Components for Lowland Britain

Geosphere-biosphere Sub-system Component	Component Description in the Assessment Context	Justification
Climate and atmosphere	The climate will range from temperate at the present day to sub-tropical in the next few hundred years, but with longer term cooling. This could result in sub-arctic to temperate conditions at the end of the 2 10^5 year period, but, in the extreme, could result in a glacial episode at 1 10^5 years recovering to temperate conditions at about 1.1 10^5 years and a subsequent slow cooling. There is a limited marine influence on atmospheric characteristics.	Long-term climate modelling conducted within BIOCLIM [2004].
Geographical extent	Local area of a few square kilometres to a few tens of square kilometres where the radionuclide plume emerges into the Quaternary sediments.	Based on the spatial extent of the proposed geological disposal facility and the likely degree of dispersion of the plume in the overlying rock.
Location	Inland site in Lowland Britain.	Defined in the assessment context.
Topography	Undulating lowland, where lines of low hills are separated by broad open valleys and where 'islands' of upland break the monotony of the more level areas.	See description of Lowland Britain given in the text.
Human community	Small rural communities making maximum reasonable use of local foods are most relevant for defining PEGs.	From consideration of endpoints of the assessment in the assessment context.
Near-surface lithostratigraphy	Quaternary sediments of complex geometry comprising layers and lenses that will often have been disturbed by post-depositional processes.	Examination of Quaternary maps of Britain [British Geological Survey, 1977a].
Water bodies	Surface water bodies are mainly flowing rivers and streams. Substantial lakes and wetlands are uncommon, but do occur. Perched aquifers may be present in the Quaternary deposits. The regional water table may either be located within the underlying bedrock or within the Quaternary deposits. In some contexts, the Quaternary deposits may act to confine a regional aquifer exhibiting artesian conditions.	Based on the description of Lowland Britain given in the text. See also British Geological Survey [1977b].
Biota	Intensively farmed environment. Cereal crops, root crops and green vegetables are grown. Fruit growing is practiced extensively, with different areas specialising in soft fruits and tree fruits. In the lower areas, arable land extends over the ridges, as well as occurring in valley bottoms. Grasslands are more common on the higher ridges of the chalk downlands, but, even there, arable agricultural activities can be observed. Sheep grazing is characteristic of these higher areas, but the rearing of cattle for milk and meat is more characteristic of the lowland pastures. Small herds of goats are kept. However, most goats are kept in small numbers domestically. Pigs are reared commercially and domestic fowl are reared both commercially and domestically.	Based on the description of Lowland Britain given in the text.

Propagation of Environmental Change to the Local Level

Step 2 in the methodology requires determination of whether environmental change needs to be taken into account in defining the GBI. If so, then global and regional changes have to be propagated to the local level. From the assessment context, it is determined that the range of climatic and landscape characteristics applicable over the next 2 10^5 years are to be taken into account, with human societal characteristics being as they are at the present day, but adapted to the climate conditions by reference to present-day societal characteristics at analogue locations.

The global and regional changes to be addressed are shown in Figure B.2. Volcanism is not an issue in a UK context. Also, orogeny, large meteorite impacts and large seismic events are extremely unlikely to occur in a British context within the next 2 10^5 years. Therefore, for the purposes of this illustrative analysis, attention is focused on global climate change, as influenced by human and natural factors, the effects of such global climate change on continental ice sheets and global sea level and hence on the regional EFEPs shown in Figure B.2.

This requires first that the regional response should be described and that it should then be propagated down to the local level. In the context of this illustrative example, which relates to a generic assessment for an inland site in Lowland Britain, the distinction between regional and local changes is less distinct than would be the case for a site-specific assessment.

The regional response is determined by studies outwith those specific to the GBI. These may involve the use of global climate models coupled to models of ice-sheet development, global sea-level and isostatic response to both ice and water loading. Alternatively, the regional response may be based on palaeoenvironmental indicator data, e.g. relating to the last glacial-interglacial cycle (MIS 5e through to the present day). For the purpose of this illustrative study, the assessment of regional conditions is based on the modelling studies reported in BIOCLIM [2004]. This involved global climate/ice-sheet/sea-level simulations using Earth Models of Intermediate Complexity (EMICs) and downscaling of the climate to a regional/local scale mainly using a rule-based downscaling procedure (model-based and statistical downscaling techniques were also investigated and were used to inform the rule-based approach, but only to a limited degree). Results of this process for Central England are described below.

Regional Climate Regime

Based on both EMIC results and snapshot calculations using Atmosphere-Ocean General Circulation Models (AOGCMs), BIOCLIM [2004] concluded that overall, for scenarios involving a significant anthropogenic contribution to greenhouse-gas-induced warming, it seems reasonable to assume that, over the next few hundred years, mean annual temperatures in Lowland Britain will increase from about 10°C to between 13°C and 16°C. The seasonal variation in temperature (warmest month – coldest month) may remain as it is at the present day (~ 12°C) or may weaken slightly (to ~ 9°C). Winter precipitation could be only marginally higher than it is at the present day, or increase by as much as 1 to 2 mm d^{-1}. In contrast, precipitation in summer is likely to decrease by 0.2 to 1.4 mm d^{-1}.

Again based on both EMIC and snapshot modelling studies, BIOCLIM [2004] concluded that following a peak in mean annual temperature over the next few hundred years, a cooling trend will ensue, such that temperate conditions similar to those of the present day will recur at between 60 ka and 160 ka AP in the scenarios involving a significant anthropogenic contribution to greenhouse-gas-induced warming. Thereafter, there is no strong trend in climate through to 200 ka AP, though there could be a brief cold episode in the range of EC to EO conditions at around 175 ka AP, with those conditions persisting for a few thousand years.

The main climatic change associated with the return to temperate conditions at between 60 ka and 160 ka AP, is a general cooling throughout the year of between 3 and 6°, with any changes in seasonality being very limited. Winter precipitation may decrease somewhat and summer precipitation is likely to increase, so that the current pattern of precipitation being reasonably uniformly distributed throughout the year is recovered. There may then be further cooling to a ‘boreal’ episode lasting a few thousand years around 175 ka AP. This would be associated with mean annual temperatures ~ 0°C, with a maximum mean monthly temperature of 10 to 18°C in July or August, and a minimum mean monthly temperature of -1 to -20°C in January. The total annual precipitation during this colder episode is expected to be very similar to that at the present day and also relatively uniformly distributed throughout the year. However, modest maxima in mean monthly precipitation either in winter or in summer may occur.

Overall, as BIOCLIM [2004] points out, the period from the present day through to 170 ka AP is characterised by a climate that is only moderately warmer than at the present day and that is associated with a similar degree of water availability throughout the year, though with somewhat drier summers. As BIOCLIM [2004] comments, the main factor in landscape evolution over this period is not climate change relative to the present day, but the duration of the period of interglacial conditions that is projected to occur. The last interglacial (OIS 5e; the Eemian) lasted 10 to 15 ka, and this is thought to be characteristic of full interglacial episodes in the Late Quaternary (i.e. since MIS 12 at around 440 ka BP). A period of interglacial conditions lasting 180 ka (from the beginning of the Holocene at around 10 ka BP to 170 ka AP) is unprecedented for Central England during the Quaternary. However, because some parts of the area of interest were beyond the margins of the British ice sheet at the Last Glacial Maximum (MIS 2 at around 18 ka BP) and have not been glaciated since the peak of the Anglian glaciation (attributed to MIS 12 at around 440 ka BP), information exists relevant to long-term rates of generalised denudation and incision of such a landscape (see below). However, in using this information, due account has to be taken of the colder conditions that persisted through much of the period.

BIOCLIM [2004] also investigated a scenario in which there was not a significant degree of global warming associated with anthropogenic greenhouse-gas emissions. Although such a scenario is highly improbable, it does provide a useful illustration of the future pattern of climate that might occur if the climate system is much less sensitive to greenhouse-gas emissions than is currently postulated. In this scenario, application of rule-based downscaling to the results from the MoBidiC EMIC leads to the projection that temperate conditions similar to those at the present day will persist for the next 50 ka. At that time, a cooling transition to Köppen-Trewartha class EO conditions is projected to occur. These conditions are projected to persist until around 100 ka AP. At that time, a rapid cooling through class EC to full glacial conditions (class FT) is projected to occur. Those glacial conditions are estimated to last for only a few thousand years before amelioration in climate occurs, recovering to temperate conditions by about 120 ka AP. Thereafter, a general cooling trend ensues, with class EO conditions from about 140 to 155 ka AP, a brief amelioration to temperate conditions to 160 ka AP, then a cooling through EO to EC conditions at 200 ka AP.

Regional Ice-sheets and Glaciers

The British Isles are unglaciated at the present-day. Based on the BIOCLIM [2004] climatic studies for scenarios involving a significant anthropogenic contribution to greenhouse-gas-induced warming, conditions would never be colder than 'boreal' at around 175 ka AP. Therefore, there is no reason to include regional ice-sheets or glaciers in the description of the environment applicable out to 200 ka AP. Even in the scenario in which there was not a significant degree of global warming associated with anthropogenic greenhouse-gas emissions, full glacial conditions were only projected to occur for a few thousand years at around 100 ka AP. During such an episode, it is likely that corrie glaciers would form in upland areas such as Western Scotland and Cumbria, and ice caps might even develop in these areas. However, the duration of the episode would be too short for those ice caps to grow into extensive ice sheets. Therefore, the degree of ice-loading of the crust would be very limited and there would be no advance of ice over lowland areas. A reasonable model for such an episode might be the Loch Lomond Stadial which correlates with the Younger Dryas, a geologically brief (1,300±70 years) period of cold climatic conditions and drought that occurred between approximately 12,800 and 11,500 years BP.

The characteristics of the Loch Lomond Stadial have been summarised by Clayton [1994]. During this episode an ice cap reformed over Scotland, corrie glaciers reformed in many of the western highlands, and, in Scotland, glacioisostatic depression was reinitiated. The Scottish ice cap was quite substantial and the ice thickness over Rannoch Moor may have exceeded 400 m. Ice also covered other areas of the Grampians and the higher western isles, such as Mull and Skye. In addition to the main ice cap, some 200 other ice masses have been mapped in the Scottish Highlands and Inner Hebrides, three of them large enough to be classified as ice caps.

In Ireland, this episode is known as the Nahanagan Stadial. Up to 32 corrie glacier moraines and protalus ramparts have been identified in Ireland and attributed to this Stadial. Most, if not all, of these corrie glaciers were smaller than a square kilometre in area.

Glaciers also reformed or extended in the wet uplands of Western Britain during this episode. In the Brecon Beacons in South Wales several corries (cwms) were occupied by ice and moraines formed. In Snowdonia and the Lake District many corries were also occupied. Small corrie glaciers (assisted by windblown snow) also developed in North-west Yorkshire.

Even if the glacial event at 100 ka AP, were more prolonged than the Loch Lomond Stadial, Lowland Britain would not be significantly impacted by an ice sheet. At the Last Glacial Maximum (around 18 ka BP) following several tens of thousands of years of cooling conditions, the British ice sheet was largely restricted to Upland Britain [see Figure 1.1 of Clayton, 1994]. Only during the Anglian Glaciation at around 440 ka BP (MIS 12) did the ice extend as far south as Bristol and London, when it laid down the extensive Quaternary deposits that remain exposed at the surface throughout East Anglia.

Regional Isostacy

From the discussion of regional ice sheets provided above, it is clear that isostatic depression of Lowland Britain will not be a major factor influencing landform development over the next 200 ka. Furthermore, little residual uplift remains to be expressed from the ice loading that occurred at the time of the Last Glaciation. Indeed, relative sea-levels have been approximately constant around the British coastline for approximately the last 6 ka, i.e. throughout the Late Holocene global sea level highstand [Shennan *et al.*, 2006].

Regional Landform and Sea-level

As noted above, in the scenario characterised by significant anthropogenically induced greenhouse-gas warming, the period from the present day through to 170 ka AP is characterised by a climate that is only moderately warmer than at the present day and that is associated with a similar degree of water availability throughout the year, though with somewhat drier summers. Over this period, the main factor in landscape evolution is not climate change relative to the present day, but the duration of the period of interglacial conditions that is projected to occur.

However, as noted above, some parts of the area of interest have not been glaciated since the peak of the Anglian glaciation at around 440 ka BP, so information exists relevant to long-term rates of generalised denudation and incision of such a landscape, provided that due account is taken of the colder conditions that persisted through much of the period.

As discussed in BIOCLIM [2004], subsequent to a glacial episode, the resultant sheet of unconsolidated deposits (often termed 'till') is subject to a continuing process of erosion. Based on reconstructions of the palaeosurfaces of till sheets formed in Northumbria, in the North-west of England, at the time of the Last Glaciation (with till formation at around 15 ka BP) and in East Anglia at the time of the Anglian Glaciation (around 440 ka BP), it is thought that the lowering of interfluves has been by no more than 1 to 2 m. In contrast, depths of valley incision due to fluvial erosion have been considerable. In the case of the Anglian till, maximum depths of valley downcutting are several tens of metres, though they do not exceed 60 m. The average depth of erosion across the whole area studied was 16.91 m and the modal depth of erosion was 10.46 m. The average depth of erosion corresponds to a rate of 38 mm ka^{-1}. In the case of the Northumbrian till, some caveats on the available data are appropriate. These are that the till does not fully clothe the solid rocks and that, whereas the rivers of the Anglian till originate within the domain that was studied, those of the Northumbrian till rise beyond the till sheet and cross it to the sea. Nevertheless, it is relevant to note that, for the whole of the Northumbrian till, the maximum depth of incision is 47.1 m, the average depth of incision is 11.85 m and the modal depth of incision is 7.46 m. These results indicate that incision into a till sheet is likely to occur mainly during the first few thousands to tens of thousands of years after it is deposited. This effect occurs for two reasons. First, the post-glacial surface hydrological regime tends to be very active, with copious amounts of available surface water that acts as an efficient agent of fluvial incision. Second, the initial channels that are formed are far from equilibrium, so rapid downcutting occurs as streams develop equilibrium profiles graded to the local base level. Thereafter, there is limited incision and sediment loads are determined mainly by the delivery of sediments from the surface-water catchment area that are transported downstream and either deposited on the floodplain or enter the estuarine/marine environment.

On this interpretation, the additional incision of stream channels that might be expected to occur over the next 170 ka can be bounded by use of data relating to the Anglian till. In that case, the maximum depth of incision that has occurred is 60 m over 440 ka. It seems likely that about 40 m of this probably occurred within 20 ka of deposition of the till. Thus, if a maximum of 20 m of incision has occurred over the last 420 ka, the additional incision over the next 170 ka should be no more than about 8 m. It could be substantially less if streams have already achieved a close to equilibrium profile. Also, it should be kept in mind that over the last 420 ka the sea level was typically some tens of metres lower than at the present day, so the main rivers would have been graded to a lower base level throughout much of the period. On interfluves, the overall depth of denudation over the next 170 ka is unlikely to exceed 1 m, as no intervals of arid conditions are postulated that could substantially enhance Aeolian erosion. In terms of the average rate of lowering of the surface, the average depths of incision of the Anglian and Northumbrian tills of 16.91 m and 11.85 m, respectively, imply that once the early active erosion phase is complete, long-term average erosion rates are unlikely to be much in excess of 0.01 m per ka. Thus, the average depth of erosion over the next 170 ka is estimated to be 1.7 m. With up to 8 m of additional incision over the next 170 ka and 1.7 m on average, slope angles should not increase by more than about 10%. Thus, topographic changes are assessed as very limited.

In principle, one factor that could affect the above analysis is a change in sea level, as this is the ultimate determinant of base level. However, in the scenarios with anthropogenic greenhouse-gas warming addressed in BIOCLIM [2004], there is generally a smaller global ice volume throughout the next 170 ka than at the present day. Thus, sea level will be at, or a few metres above, its present level throughout the period.

Outside the river valleys, the degree of surface lowering over the period is expected to be less than 1 m. Therefore, there will be very little increase in the area of land from which till is completely removed exposing the underlying parent material. Generalised Aeolian and fluvial erosion will remove existing superficial soil horizons. However, the soil system will remain covered with vegetation, so a new organic A horizon will continually be formed and changes in the soil profile are expected to be very limited. In the river valleys, several metres of erosion could result in removal of the till in some areas and the establishment of new hydraulic connections between surface waters and the underlying rock. It seems unlikely that the nature and extent of alluvial deposits would be substantially altered.However, the spatial pattern of those deposits might alter somewhat, with switching between erosional and depositional regimes being determined by detailed spatial and temporal changes in the flows of surface waters.

Losses of material by solubilisation (chemical erosion) are likely to be very limited compared with fluvial and Aeolian erosion, except, possibly, in the case of the outcrop of the Chalk east of The Fens. However, the low elevation of this Chalk outcrop is regarded as mainly due to the effects of the Anglian ice, so it seems unlikely that chemical erosion would result in lowering of that outcrop by more than a few metres over the next 170 ka.

The transition to a period of colder climate at around 170 ka AP gives rise to some additional considerations. This climate is projected to fall into either Köppen-Trewartha class EO or EC.

Climate state EO would be characterised by cool summers (mean temperature of the warmest month just over 10°C) and winter temperatures in the coldest month of between about -6°C and 0°C. The total precipitation would be very similar to that at the present day and distributed approximately uniformly throughout the year. There would be an annual moisture excess of about 200 mm and a summer moisture deficit similar to that at the present day. However, with an overall annual moisture excess and a very wet spring, it is unlikely that irrigation would be required.

Even if irrigation did occasionally occur, it would probably utilise surplus surface water, rather than groundwater.

As discussed above, the topography and near-surface lithostratigraphy would be very little altered from the present day. However, there could be some soil modification to produce gelic histosols.

In the case of the scenario without significant anthropogenically induced greenhouse-gas warming, the main additional consideration is the glacial episode at around 100 ka AP. The glacial episode is entered by a rapid (less than 3.5 ka) transition through EC conditions and then persists for about 5 ka or a little longer. The following FT state is characterised by a mean annual temperature of about -5°, a seasonal range in which the mean temperature of the coldest month is typically -5 to -20°C and the mean temperature of the warmest month is about 7°C, and an annual precipitation of about 700 mm distributed reasonably uniformly throughout the year. A caveat should be noted on these climate characteristics. Palaeoenvironmental data suggest that Lowland Britain experienced intensely cold winters during previous episodes of polar tundra (FT) conditions. This suggests that the temperature of the coldest month should be assessed as about -20°C and that a temperature approaching -5°C is substantially too high. However, set against this, the limited development of northern hemisphere ice associated with this episode will mean that Lowland Britain is not in an ice-marginal location, as it was at the Last Glacial Maximum.

The mean annual temperature of this state is consistent with the development of discontinuous permafrost in Lowland Britain. This is in agreement with the palaeoenvironmental record, as relict permafrost features are observed in those areas that were within the margin of the Anglian ice sheet but outside the margin of the Late Devensian (Last Glaciation) ice. Indeed, it is likely that discontinuous permafrost would begin to develop during the latter part of the preceding EC climate state. However, the short duration of that state makes this of only very limited significance. In addition to the permafrost, seasonal freezing and thawing of the overlying soils and sediments would occur. Thus, cryoturbated soils and other frozen ground effects would be induced.

Regional Land Use, Vegetation and Soils

As argued above, only limited changes would be expected in the types of soil profile present. Therefore, the main controls on vegetation and land use would be climatic.

As discussed in BIOCLIM [2004], under the warmer climate conditions expected to occur in the scenarios with significant anthropogenically induced greenhouse-gas warming and with irrigation, a wide range of crops could be grown, as at the present day. Furthermore, there is also no reason why animal husbandry practices should be very different from those of the present day, except that pasture might be irrigated and animals would be able to graze such irrigated pasture throughout the year. As the climate cooled, patterns of agriculture would not be expected to change markedly, but there would be some reduction in the demand for irrigation. Also, there is good reason to consider that the landscape would continue to be fully utilised for human activities throughout the warming and cooling phases considered herein, i.e. no increase in the extent of natural and semi-natural biotic communities needs to be taken into account.

Beyond 170 ka AP and under EO or EC conditions, a largely treeless landscape is likely to develop, either from forested or unforested antecedent conditions (this also applies to the FT state projected to arise in the scenario without significant anthropogenically induced greenhouse-gas warming at around 100 ka AP). Agriculture would be largely animal husbandry, with land given over to grass for either summer grazing or hay production. Animals would be over-wintered indoors. Arable cultivation would mainly be of vegetables, with barley grown in areas with the least severe climate. Extensive areas of natural vegetation are likely to develop, i.e. the spatial extent of utilisation of the landscape by humans is likely to decrease. This natural vegetation would comprise mainly various types of low-growing shrubs (tending to tundra-type vegetation in EC conditions). With a low productivity agricultural system based on livestock husbandry, small villages, hamlets and isolated homesteads widely dispersed over the rural landscape are likely to be the characteristic human communities. However, it would be possible to sustain a mix of urban and rural communities as at the present day.

Regional Hydrology, Hydrogeology and Hydrogeochemistry

With the limited changes in topography projected over the next 170 ka and the limited changes in either amounts of precipitation or seasonal temperatures, it seems unlikely that there would be substantial changes in the pattern of surface water flows or in groundwater levels. Thus, the overall surface and near-surface hydrological system is likely to be very similar to that at the present day. These remarks reflect the maturity of the landscape. However, it is noted that substantial changes in hydrology could occur as a consequence of human activities. At an inland site, the groundwaters present in the Quaternary deposits are likely to exhibit a chemical composition characteristic of recent meteoric water.

Beyond, 170 ka AP, the EC climate that could occur is typically characterised by warmer summers than EO and much colder winters. Overall, this results in a mean annual average temperature about 5°C colder. It is debatable whether this extreme contrast in continentality would apply in Lowland Britain, though it might arise as a result of changes to ocean circulation patterns in the northeast Atlantic. If an EC climate were to occur, substantial changes to water bodies would be expected. Very cold winters would lead to extensive snowpack development and the freezing of rivers. The spring melt would be associated with ice dams in the rivers and very high peak flows. In consequence, there would be considerable remodelling of river channels. Similar effects would be expected under the FT conditions postulated to occur in the scenario without significant anthropogenically induced greenhouse-gas warming.

Discontinuous permafrost would be present, overlain by a seasonal active layer. Soil structures, such as ice wedges, that are characteristic of cold regions would be expected to form.

Regional Atmosphere

No substantial changes in the regional atmosphere are projected to occur.

Propagation of the Regional Changes to a Local Level

It is first relevant to note that under both of the scenarios with and without significant anthropogenically enhanced greenhouse warming, sites in Lowland Britain are likely to be well beyond the margins of any ice caps that are present. Therefore, for illustrative purposes, it is sufficient to consider a site subject to anthropogenically enhanced greenhouse warming leading to a period of sub-tropical to temperate conditions out to 170 ka AP. Thereafter, cooling through EO to EC/FT conditions can be assumed.

The site can be assumed to be located within the boundaries of a surface-water catchment or sub-catchment with an area of a few tens of square kilometres (i.e. large enough to receive the radionuclide plume arising from the geological disposal facility). Over the 200 ka period being considered, the interfluves bounding that catchment will be lowered by less than 1 m and the stream and river channels present within it will deepen by up to 8 m, but generally by rather less than this.

The lithostratigraphy of the catchment comprises a mixed sequence of unconsolidated Quaternary deposits overlying weathered bedrock. Deeper groundwaters discharge from the weathered bedrock over at least part of the catchment area and they mix with recent meteoric waters within the Quaternary sediments. The deeper groundwaters may be confined in some areas and artesian conditions can develop. Stream and river channels are mainly developed in the Quaternary deposits, but can be incised through to the weathered bedrock at some locations, and the extent of such incision may increase with time due to the deepening of the stream and river channels. The stream and river channels may include both discharging and recharging sections along their lengths, with the extent of the discharge and recharge sections varying seasonally and altering as the climate changes.

Over the first 170 ka of the assessment period, the entire area of the surface-water catchment can be taken to be utilised for intensive agriculture (both arable and animal husbandry), but with a local community present that also undertakes garden cultivation of fruit and vegetables, and rears various types of animals, including hens, goats and pigs. The main changes over this period will be in relation to irrigation requirements that will be determined by the types of crops being grown and the current climate. Soil characteristics will not alter substantially over this period.

Beyond 170 ka AP, the cooling climate will result in a gradual reduction in the extent of agriculture. The catchment will become increasingly dominated by a low shrub, semi-natural vegetation with the eventual outcome being tundra-type vegetation. In the earlier part of the period, seasonal freezing of the superficial soil layers will occur and gelic histosols will begin to develop. In the latter part of the period, discontinuous permafrost will begin to develop and will eventually penetrate through the full depth of the Quaternary deposits. It will be overlain by a seasonally active layer not more than about one metre deep. Also in the latter part of the period, very cold winters will lead to extensive snowpack development and the freezing of rivers. The spring melt will be associated with ice dams in the rivers and very high peak flows. In consequence, there will be considerable remodelling of river channels, but the overall depth of incision will not exceed 8 m.

Narratives for Qualitatively Different Futures

In the example described here, it has been possible to condense all the environmental changes of relevance identified in scenarios with and without significant anthropogenically induced greenhouse-gas warming into a single narrative, as provided immediately above. The one omission from this narrative is an account of the transition from an EC/FT climate to an interglacial (DO) climate. However, this could be addressed by extending the narrative out somewhat beyond 200 ka AP. Thus, a conclusion from this analysis is that, in this case, the safety assessment can proceed on the basis of a single narrative.

Preferred Approach to Representing Environmental Change

In broad terms, the narrative set out above corresponds to a sub-system with a time-independent geometry over the first 170 ka, but with water flows that change with time according to the prevailing climate. However, there is one exception to this, in that a significant degree of stream incision may occur over the period. Therefore, setting aside the initial warming transition (which takes place over a few hundred years), it seems useful to distinguish the first 170 ka into two states (S1 and S2) with an extended transition (T1) between them. The two states are briefly summarised in Table B.12, using the standard set of GBI components.

Table B.12: States of the Geosphere-biosphere Sub-system that are taken to be Applicable over the First 170 ka

Component	Description for S1	Description for S2
Climate	Mean annual temperature 13°C and 16°C (3°C to 6°C warmer than at the present day). The seasonal variation in temperature (warmest month – coldest month) may remain as it is at the present day (~ 12°C) or may weaken slightly (to ~ 9°C). Winter precipitation could be only marginally higher than it is at the present day, or increase by as much as 1 to 2 mm d^{-1}. In contrast, precipitation in summer is likely to decrease by 0.2 to 1.4 mm d^{-1}.	DO climate, as obtained from climate stations in Lowland Britain at the present day.
Atmosphere	As at the present day.	As at the present day.
Topography	As at the present day.	As at the present day, except that stream and river channels are incised by up to 8 m. Incision of minor streams should be only a small fraction of 8 m, whereas incision of the main river channel should grade to a maximum of about 8 m at its outlet from the catchment.
Near-surface lithostratigraphy	As at the present day.	As at the present day except for the effects of incision. Sediments removed by incision are assumed to be lost from the catchment in suspension in flowing surface waters.
Water bodies	Surface water flows and groundwater recharge rates adapted from present day values to allow for the effects of the warmer climate on effective precipitation. Presence and extent of perched water bodies adjusted accordingly.	Surface water and groundwater flows and the distribution of perched water bodies identical to those at the present day.
Biota	Intensive agriculture and garden cultivation, as at the present day.	Intensive agriculture and garden cultivation, as at the present day.

The extended transition T1 from S1 to S2 is defined in terms of three major factors:

- A cooling of climate;
- An extended period of incision with the eroded sediments being lost from the catchment in river flow;
- An adaptation of the surface-water and groundwater flow systems to the changing climate and altered hydraulic connectivity resulting from the incision.

Beyond 170 ka AP, the cooling that occurs within the remainder of the 200 ka period for which the narrative is defined is distinguished into two further states (S3 and S4) and two further transitions (T2 and T3). The two states are described in Table B.13.

Table B.13: States of the Geosphere-biosphere Sub-system that are taken to be Applicable between 170 ka and 200 ka AP

Component	Description for S3	Description for S4
Climate	EO climate characterised by cool summers (mean temperature of the warmest month just over 10°C) and winter temperatures in the coldest month of between about -6°C and 0°C. The total precipitation would be very similar to that at the present day and distributed approximately uniformly throughout the year. There would be an annual moisture excess of about 200 mm and a summer moisture deficit similar to that at the present day.	EC/FT climate characterised by a mean annual temperature of about -5°, a seasonal range in which the mean temperature of the coldest month may be as low -20°C and the mean temperature of the warmest month is about 7°C, and an annual precipitation of about 700 mm distributed reasonably uniformly throughout the year.
Atmosphere	As at the present day.	As at the present day.
Topography	As at the present day, except that stream and river channels are incised by up to 8 m. Incision of minor streams should be only a small fraction of 8 m, whereas incision of the main river channel should grade to a maximum of about 8 m at its outlet from the catchment.	As at the present day, except that stream and river channels are incised by up to 8 m. Incision of minor streams should be only a small fraction of 8 m, whereas incision of the main river channel should grade to a maximum of about 8 m at its outlet from the catchment.
Near-surface lithostratigraphy	As at the present day except for the effects of incision.	As at the present day except for the effects of incision.
Water bodies	Surface water flows and groundwater recharge rates adapted from present day values to allow for the effects of the colder climate on effective precipitation. Presence and extent of perched water bodies adjusted accordingly. Seasonal ground freezing occurs, but there is no permafrost development. Ice formation in rivers affects the surface water flow regime.	Surface water flows and groundwater recharge rates adapted from present day values to allow for the effects of the colder climate on effective precipitation. Presence and extent of perched water bodies adjusted accordingly. Discontinuous permafrost is present throughout the depth of the Quaternary deposits and overlain by a seasonal active layer. Ice formation in rivers affects the surface water flow regime.
Biota	Mainly animal husbandry, with some areas of semi-natural scrub vegetation.	Tundra-type semi-natural vegetation.

The two transitions, T2 and T3 are from S2 to S3 and from S3 to S4, respectively. The transition T2 is defined in terms of:

- A cooling in climate from DO to EO conditions;
- No changes in atmosphere, topography or lithostratigraphy (as incision is addressed in T1);
- The introduction of seasonal freezing of the surface waters and the superficial ground layer;
- A change from intensive agriculture and gardening to mainly grassland for animal husbandry and an increased area of semi-natural shrub vegetation;
- Modifications to the surface water and groundwater flow regimes corresponding to these changes.

The transition T3 is defined in terms of:

- A cooling in climate from DO to EC/FT conditions;
- No changes in atmosphere, topography or lithostratigraphy;
- The gradual development of discontinuous permafrost to depth beneath a seasonally frozen active layer;
- Intensification of the seasonal freezing of surface waters;
- Abandonment of agriculture and development of natural tundra vegetation;
- Modifications to the surface water and groundwater flow regimes corresponding to these changes.

The periods of the states and transitions are not defined in the above, nor need they be at this conceptual stage. However, for guidance, the periods shown in Table B.14 are considered to be realistic. These allow a long period for incision to occur and also provide an extended period (15 ka) for permafrost to develop to depth.

Table B.14: Illustrative Durations for the States and Transitions of Interest.

State or Transition	Period (ka AP)	Duration (ka)
S1	0-40	40
T1	40-130	90
S2	130-170	40
T2	170-175	5
S3	175-180	5
T3	180-195	15
S4	195-200	5

Interaction Matrices for the Geosphere-biosphere Sub-system

Having identified the four states S1, S2, S3 and S4, the next step is to develop interaction matrices showing the processes operating between the individual components of the GBI for each of those states. The interaction matrix for state S1 is shown in Figure B.19. Note that this corresponds closely to the illustrative example shown in Figure B.4, but adjusted to be applicable to a general regional aquifer (not necessarily in underlying chalk) and removing effects of incision, as these do not occur in time-independent state S1.

Köppen-Trewartha climate state DO (temperate oceanic)	Determines seasonal temperatures and precipitation. Relative humidity generally relatively high. Most precipitation falls as rain rather than snow.	No incision occurs	No significant influence on structures, as ground freezing is of negligible importance.	No significant influence.	Seasonal temperatures and precipitation define flow rates in all components of the surface-water system. The baseflow in the main river channel is determined by longer-term variations in climate, being governed by discharge from the underlying aquifer.	Seasonal temperatures and precipitation govern the water content of soils and perched aquifers. Relatively wet summers mean that only limited drying of soils occurs in the summer months.	Seasonal temperatures and precipitation govern the recharge of the underlying aquifer from areas close to local interfluves, but the main recharge of this aquifer occurs at a broader regional scale.	Seasonal temperatures and precipitation determine a moderate irrigation requirement in some, but not all, years.
No significant influence.	**Low to moderate levels of atmospheric pollution. Generally low dust loads. Limited influence of marine aerosols (inland site assumed).**	No significant influence.	No significant influence.	No significant influence.	No significant influence	Influence on hydrochemistry negligible compared with the effects of agricultural practice.	Influence on hydrochemistry negligible compared with the effects of agricultural practice.	No significant influence.
Minor differences in climate between the river valleys and the more exposed palaeosurface into which they are incised.	Minor differences in pollution and dust loads between the valleys and the interfluves.	**Subdued topography. V-shaped river valleys incised to a depth of a few tens of metres and sometimes penetrating through the Quaternary sediments to the underlying weathered rock.**	Incision penetrates through the layered Quaternary sequence and into the underlying aquifer. No erosion is occurring, so the exposed strata and the hydraulic connections between them are not being modified.	Incision penetrates through the layered Quaternary sequence and into the underlying aquifer. No erosion is occurring, so the exposed strata and the hydraulic connections between them are not being modified.	Overall topography controls the spatial pattern of small streams and the main river channel. This is stable over time.	The locations of the phreatic surfaces in the unconfined aquifers are controlled both by the overall topography and the layered structure of the Quaternary deposits.	The artesian conditions in the aquifer are controlled mainly by regional influences and not by the local topography.	Pasture is favoured in riparian areas in the river valleys, with arable agriculture favoured higher up the valley sides and on the plateau. Woodland is confined to the more sheltered areas in the valleys, with individual trees and hedgerows (as field boundaries) more characteristic of higher ground.
No significant influence.	No significant influence.	No incision occurs	**Complex sequence of Quaternary sands and clays with a laterally extensive layered structure, but with connections of high hydraulic connectivity between layers of high hydraulic conductivity otherwise separated by aquitards.**	The interface between the Quaternary deposits and the underlying weathered rock is not well defined, with later sediments penetrating into the upper weathered zone of the chalk.	The characteristics of the sequence define whether the stream and river channels are recharge or discharge boundaries. The pattern of drainage ditches is also determined by local drainage characteristics of the soils and underlying sediments.	The locations of the phreatic surfaces in the unconfined aquifers are controlled both by the overall topography and the layered structure of the Quaternary deposits. The hydrochemistry of the aquifer waters will be partly determined by the physico-chemical properties of the deposits.	The Quaternary deposits are taken to confine the underlying aquifer, but areas of higher conductivity in these deposits define locations of upwelling and discharge.	Soil texture and drainage influence the use of land for arable agriculture or pasture.
No significant influence.	No significant influence.	No significant influence.	The interface between the Quaternary deposits and the weathered rock is not well defined, with later sediments penetrating into the upper weathered zone.	**Weathered rock underlying the Quaternary deposits**	No significant influence of the geology on surface drainage systems, except that the regional aquifer in the weathered rock will constitute a discharge boundary for parts of the main river channel.	Indirect connectivity to perched aquifers through the overlying Quaternary sediments.	Defines the porosity and hydraulic conductivity of the confined aquifer and also conditions the hydrochemistry of the groundwater.	No significant influence.
No significant influence.	No significant influence.	No incision or sedimentation.	No incision or sedimentation.	No incision or sedimentation.	**Agricultural drainage ditches and small ephemeral streams draining to a single river channel.**	The surface water system is connected to the perched aquifers. Both recharge of these aquifers and discharge from them will occur. The hydrochemistry of the perched aquifers will be partly determined by the hydrochemistry of the recharging water.	The surface water system is directly connected to the regional aquifer in the river valley. It will mainly receive water discharged from the aquifer, so its main influence on the aquifer will be to perturb the flow field in the region of discharge rather than to alter its hydrochemistry.	Closely integrated with the agricultural practices in the area, e.g. by determining the adequacy of drainage of the field system.
No significant influence.	No significant influence.	No significant influence.	No significant influence.	No significant influence.	The surface water system is connected to the perched aquifers. Both recharge of these aquifers and discharge from them will occur. The hydrochemistry of the surface water system will be partly determined by the hydrochemistry of the discharging water.	**Perched aquifers in the Quaternary sediments.**	Hydraulic connections mainly result in discharges from the regional aquifer to the overlying perched aquifers, so its main influence on the regional aquifer will be to perturb the flow field in the region of discharge rather than to alter its hydrochemistry.	Used to extract limited amounts of water from shallow wells for human and animal drinking water and for garden irrigation.
No significant influence.	No significant influence.	No significant influence.	No significant influence.	No significant influence.	The surface water system is directly connected to the regional aquifer in the river valley. It will mainly receive water discharged from the aquifer, so the river flow rate will be affected (defining base flow) and the hydrochemistry of river waters will also be influenced.	Hydraulic connections that mainly result in discharges from the regional aquifer to the overlying perched aquifers. This will influence both the geometry of those aquifers and their hydrochemistry.	**Confined artesian aquifer in the weathered rock.**	Used to extract substantial quantities of water for commercial agricultural irrigation.
Minor influence through differential evapotranspiration from different crop types.	Minor influence through differential evapotranspiration from different crop types.	Stabilises the system against erosion and provides organic matter inputs to soil.	Stabilises the system against erosion.	No significant influence.	Fertiliser additions influence the composition of surface waters. The drainage system is maintained as an integral part of agricultural activities.	Abstraction of water results in drawdown of the water table.	Abstraction of water perturbs the flow system and may result in the introduction of oxygen into the aquifer by penetration down the borehole.	**Intensive agriculture and garden cultivation.**

Figure B.19: Interaction Matrix for State S1

In Figure B.19, the shaded cells indicate interactions that are likely to be of significance. These cells form clusters that will be relevant for the later analysis. This is illustrated in the influence diagram shown in Figure B.20.

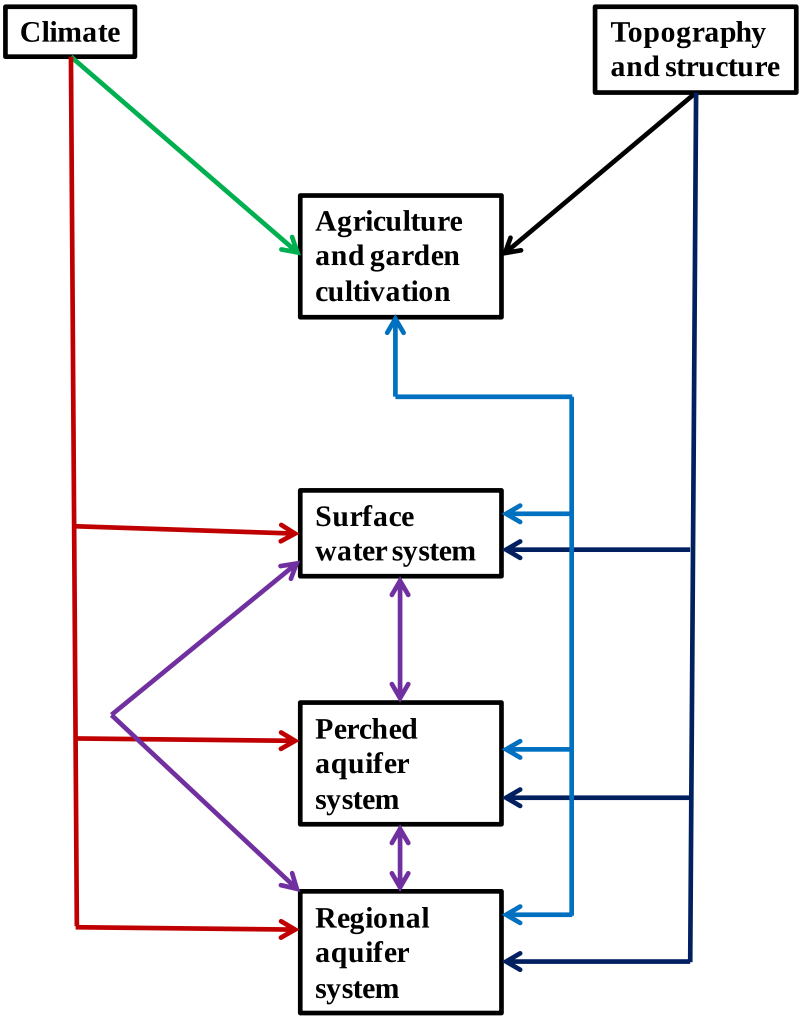


Figure B.20: Simplified Influence Diagram abstracted from the Interaction Matrix shown in Figure B.19.

Topography and structure (lithostratigraphy) are closely related to each other and are conveniently considered together. In this time-independent state in which no incision or sedimentation is occurring, the topography and structure can be defined independent of the other components of the GBI. Similarly, the local subdued topography and hydrological system have only very minor influences on the local climate, so the climate can be defined independent of the other components of the GBI.

Agriculture and garden cultivation are strongly influenced by both climate and topography, but they do not have a significant influence on those factors. In contrast, agriculture and garden cultivation strongly influence and are influenced by all components of the hydrological and hydrogeological system (largely through water abstraction). Climate also strongly affects all aspects of the hydrological and hydrogeological system, since it is the primary control on the amounts of water available. In addition, all aspects of the hydrological and hydrogeological system are closely coupled to each other.

Similar interaction matrices can be developed for states S2, S3 and S4. These only differ to a limited degree from that developed for S1.

Characterisation of the Geosphere-biosphere Sub-system in a 3D Model

This step applies to each state of the GBI that was identified in step 4 of the methodology. Here this analysis is performed for states S1 to S4. This step requires consideration not only of the components of the sub-system (which have largely already been identified), but also their geometry, their spatially distributed properties and the processes that operate within and between them. Because of this emphasis on geometry, except for the local climate, the characterisation is most conveniently performed in terms of a sequence of 3D visualisations showing the various aspects of the GBI.

State S1

<u>Climate</u>

The climate of Lowland Britain under greenhouse-warmed conditions (Cr or Cs in the Köppen-Trewartha classification) is fully characterised in Appendix C of BIOCLIM [2004]. Under Cr conditions, the mean temperature of the coldest month is between about 5ºC and 10ºC, whereas the temperature of the warmest month is between 18ºC and 22ºC. Under Cs conditions, the mean temperature of the coldest month is between 6ºC and 14ºC, whereas the mean temperature of the warmest month is between 22ºC and 27ºC. The mean annual temperature over the analogue stations considered is slightly below 15ºC for Cr and about 17ºC for Cs. However, the Cr and Cs stations individually comprise a continuum with mean annual temperatures ranging from 10ºC to 20ºC. Thus, they encompass a sufficient range to represent the long period of cooling back down to current temperate (DO) conditions.

Precipitation in Cr conditions peaks in the winter months at about 100 to 140 mm per month and is at a minimum in July and August at about 20 to 50 mm per month. Under Cs conditions, precipitation peaks in the winter months at 50 to 200 mm per month and is low (0 to about 50 mm per month) from May to August. Averaged over all the analogue stations considered, the maximum precipitation in winter is about 120 mm per month in Cr conditions and about 100 mm per month in Cs conditions. Similarly, the minimum precipitation in summer is about 30 mm per month in Cr conditions and about 10 mm per month in Cs conditions. The annual mean precipitation in Cr conditions is approximately 1000 mm, which can be compared with about 650 mm in Cs conditions and about 630 mm in temperate (DO) conditions.

Under Cr conditions, there is very little difference between the analogue stations in terms of moisture excess or deficit (defined as precipitation minus potential evapotranspiration). In December and January the moisture excess is around 100 mm per month, dropping to zero in May. In June, July and August, there is a moisture deficit in the range 50 to 120 mm per month, but in September the moisture deficit is around zero and the moisture excess then increases during October and November back to its peak value in December. Under Cs conditions, the moisture excess in the winter months is typically 30 to 150 mm per month, but the excess falls to zero in April and does not rise above zero until October. From May to September, there is a moisture deficit that reaches approximately 150 mm per month in July.

In terms of overall annual moisture excess or deficit, there is a strong distinction between Cr and Cs conditions. In typical Cr conditions, there is an annual moisture excess of over 200 mm (compared with a near-zero excess in temperate, DO conditions). In contrast, in typical Cs conditions, there is an annual moisture deficit of around 200 mm. Thus, Cr conditions are generally rather wetter than those prevalent today, whereas Cs conditions are significantly drier, tending towards a semi-arid environment. In contrast to temperature, there is a strong distinction in precipitation between the Cr and Cs analogue stations, rather than a continuum of characteristics.

This annual distinction is also reflected in the summer (May to August) moisture deficit. This is about 240 mm in Cr conditions (compared with about 180 mm in temperate, DO, conditions), but is much larger, at about 450 mm, in Cs conditions. Thus, whereas irrigation of crops may only be required in some years in DO and Cr conditions, it would be required in almost all years in Cs conditions, and irrigation of pasture (or fodder crops) may also be undertaken. (See also Figure 3.3 in BIOCLIM [2004], which displays the contrast between annual summer soil moisture deficits at Bordeaux (Cr) and Perpignan (Cs) over the period 1950 to 1990).

<u>Topography and Lithostratigraphy</u>

The topography at the present day is that of the Anglian till, as described by Clayton [1994] and illustrated in Figure B.21.

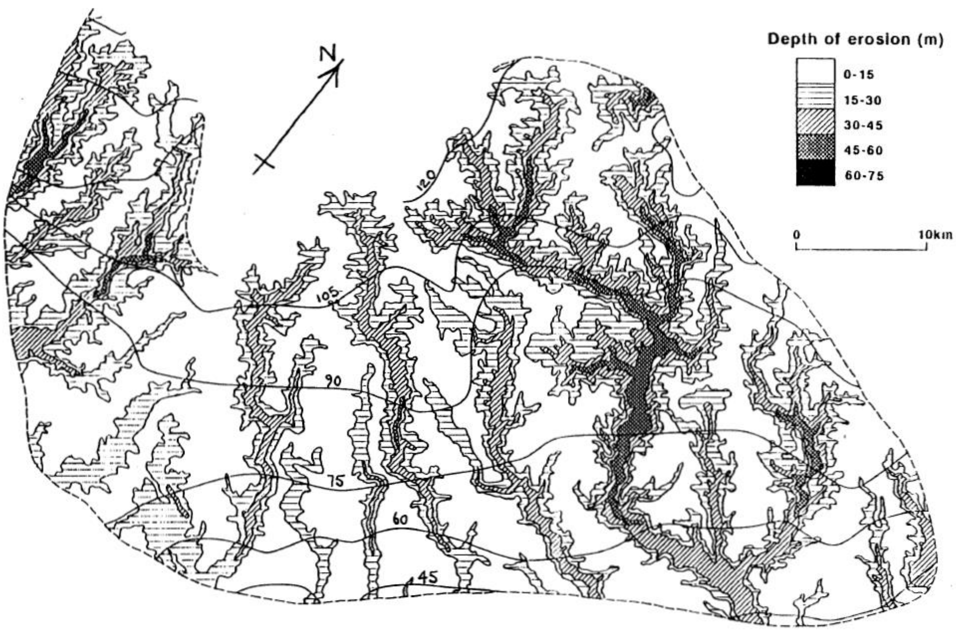


Figure B.21: Incision of the Anglian Till in Suffolk and Part of Essex. Contours of the Palaeosurface into which Incision occurred are shown at Intervals of 15 m.

Any one of the valley systems shown on Figure B.21 could be adopted as the surface-water sub-catchment into which the discharge of contaminated groundwater is projected to occur. However, for convenience, a simple V-shaped catchment might be used for illustrative purposes, with only minor channels draining into the central river valley.

The lithostratigraphy of the Anglian till is taken from the Quaternary geology map of Southern Britain (British Geological Survey, 1977a). The relevant area is illustrated in Figure B.22. Note that north is oriented differently in Figures B.21 and B.22.

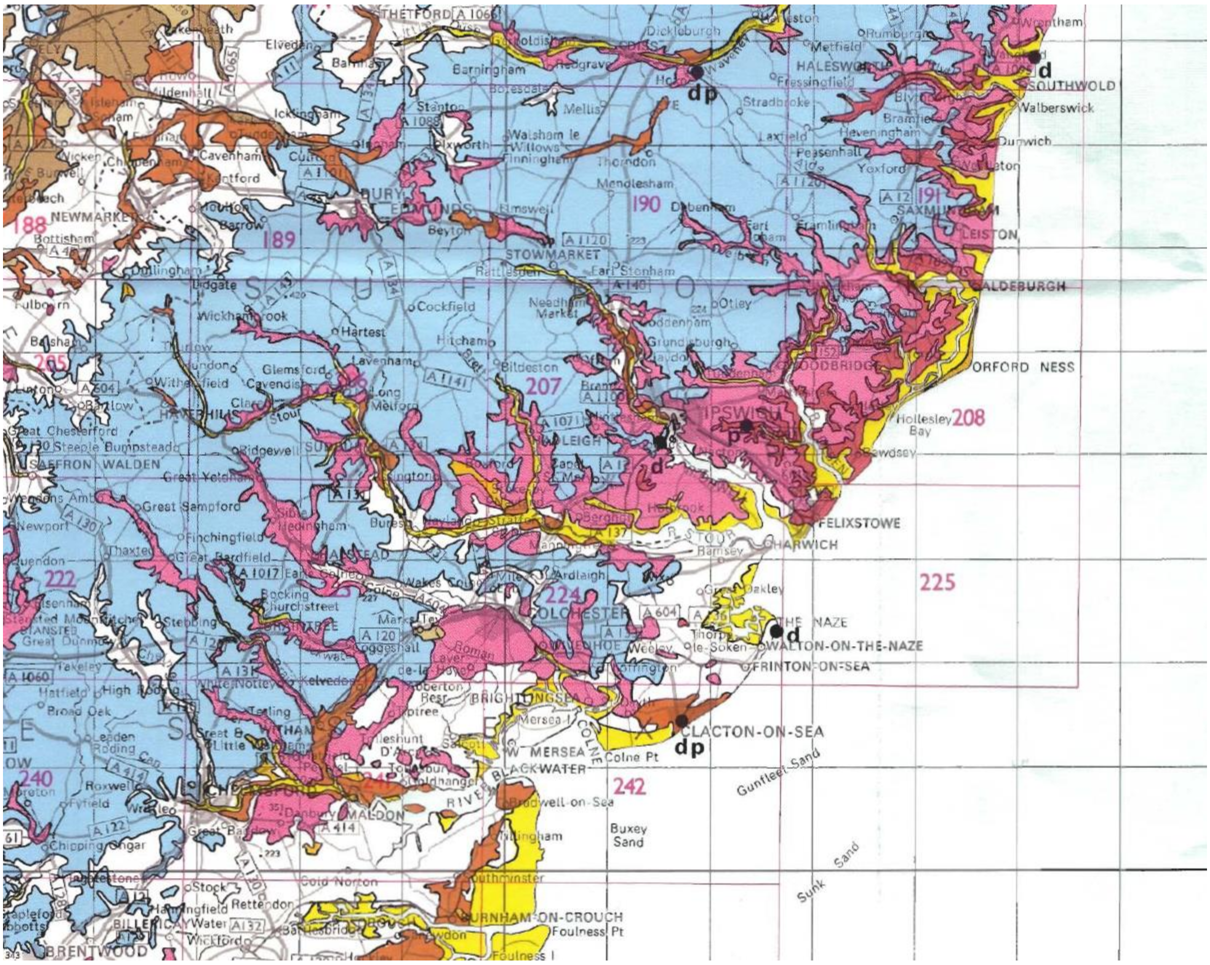


Figure B.22: The Quaternary Geology of the Anglian Till (10 km grid squares).

The upland areas (blue) are described as Boulder clay and Morainic Drift. Along the river valleys are deposits of sand and gravel of uncertain age or origin (pink) and limited areas of alluvium (yellow). The Boulder Clay and Morainic Drift is described as representing mainly ground moraine, the distinction between Boulder Clay and Morainic Drift being in places largely topographic. The definition also encompasses undifferentiated glacial drift. The deposits of sand and gravel are largely river terraces standing above the present flood plain. Most of these terraces are mainly sand and gravel, but some comprise, or are capped by, silt and clay. The underlying chalk outcrops to the northwest of the area illustrated in Figure B.22 (see Figure 11 of Stamp [1946] for a simplified geological map of Britain).

Boulder clay is a deposit of clay, often full of boulders, which is formed in and beneath glaciers and ice-sheets wherever they are found, and was the typical deposit of the Glacial Period in northern Europe and North America. Much boulder clay is of a bluish-grey until exposed to weather which causes a transformation to a brown colour. Boulder clay is classed with a group of poorly sorted materials, described by the non-genetic term diamicton. It is usually stiff, tough clay devoid of stratification though some varieties are distinctly laminated. Occasionally, within the boulder clay, there are irregular lenticular masses of more or less stratified sand, gravel or loam. The boulders are held within the clay in an irregular manner, and they vary in size from pebbles up to masses many tons in weight. Usually they are somewhat oblong, and often they possess a flat side or sole; they may be angular, sub-angular, or well-rounded, and, if they are hard rocks, they frequently bear grooves and scratches caused by contact with other rocks while held firmly in the moving ice. Like the clay in which they are borne, the boulders belong to districts over which the ice has travelled.

If a single river valley is adopted as being the sub-catchment of interest, the main Quaternary deposit should be taken to comprise boulder clay, incorporating lenses of sand, gravel or loam. Within the river channel, a terrace or terraces of sand and gravel can be included superimposed on the underlying Boulder Clay. The underlying bedrock of the region comprises mainly Neogene deposits of gravel, sand, silt and clay, but there are also areas of chalk formed during the Cretaceous (BGS Geology of Britain Viewer, http://mapapps.bgs.ac.uk/geologyofbritain/home.html). It seems reasonable to assume discharge from a chalk aquifer underlying the Boulder Clay. Based on the above analysis, an illustrative sketch of the type of catchment of interest is provided as Figure B.23.

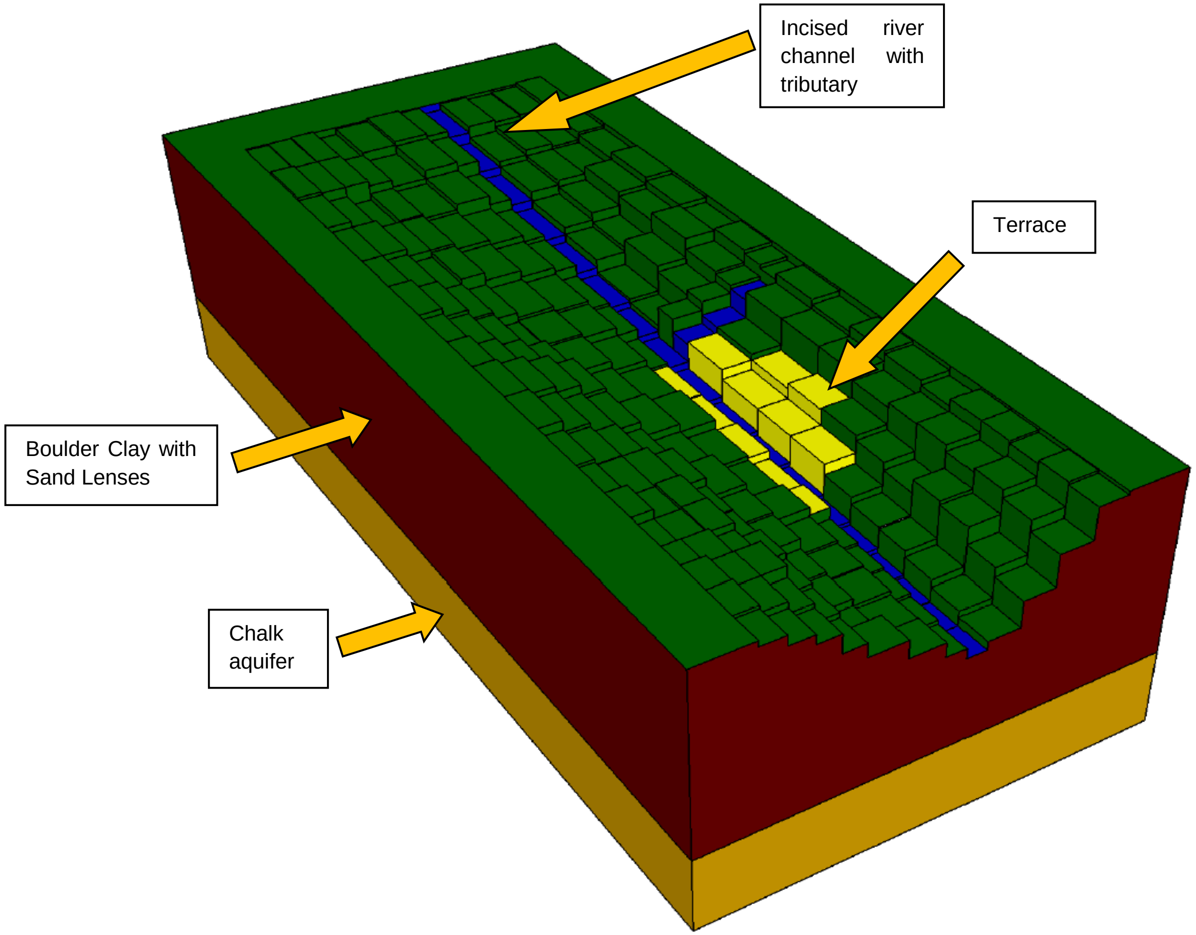


Figure B.23: Illustrative Catchment of Interest (also showing how it might be discretised in a simple finite-element model).

A typical cross-section across such a catchment is as illustrated in Figure B.24.

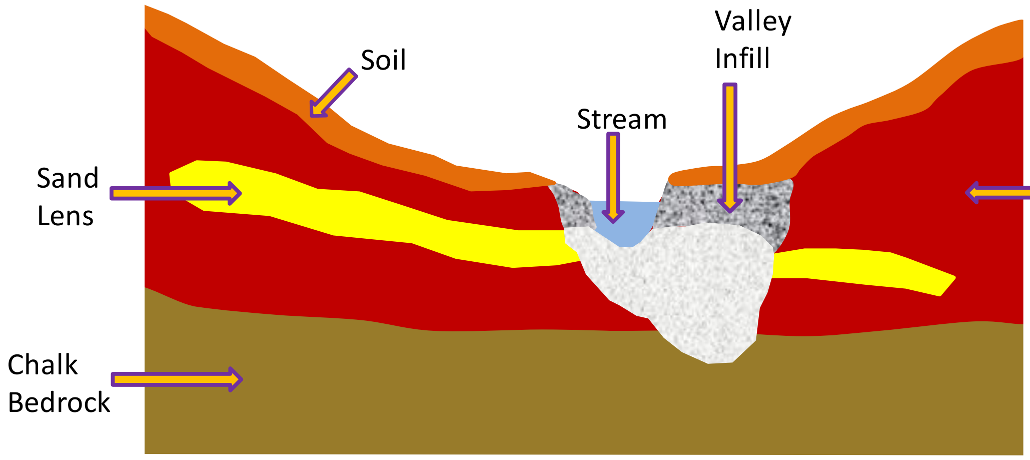


Figure B.24: Typical Cross Section of the Catchment of Interest.

<u>Surface Water and Groundwater Flow Regime</u>

Meteoric water will mainly penetrate the soil, but will tend to be deflected sub-horizontally at the interface with the boulder clay and will be transferred downslope to the stream channel or the valley infill. A limited amount may percolate through the boulder clay, but be deflected sub-horizontally in any high hydraulic conductivity layers that it encounters. In high intensity rainfall events or after prolonged wet periods, some precipitation may be transferred to the stream channel in surface runoff. The chalk is assumed to host an aquifer that is confined by the overlying boulder clay and is under artesian conditions. This leads to upwelling through the high conductivity valley infill and discharge to the stream and near-stream soils where they are underlain by the valley infill. This discharge region may not be present towards the head of the stream and the upper part of the chalk may be unsaturated in that area. Likely pathways of surface water flow are shown in Figure B.25. Similar pathways are likely to characterise interflow at the boundary between the overlying soil and the Boulder Clay. Likely pathways of sub-surface flow are shown on a section through the catchment in Figure B.26.

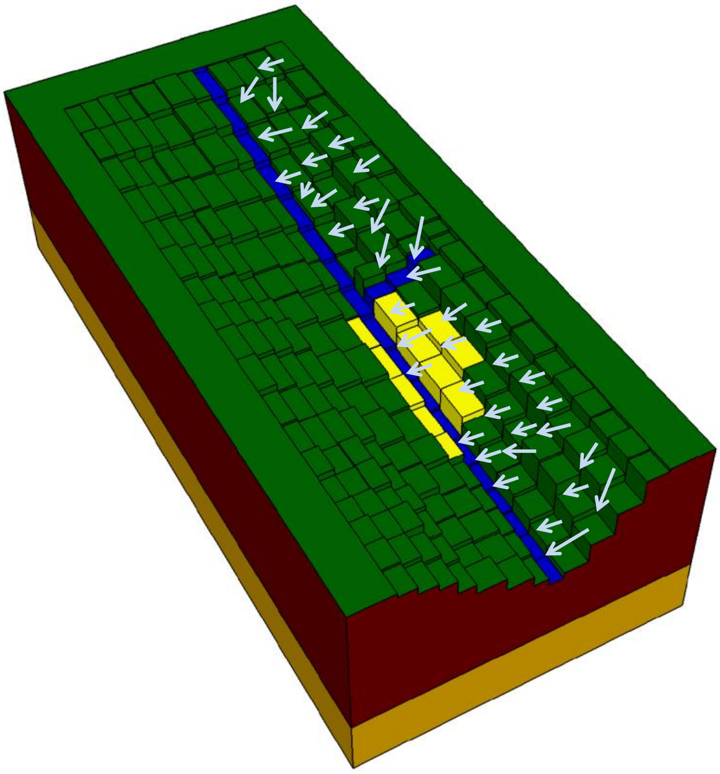


Figure B.25: Surface Water Flows (shown for one side of the catchment only)

In Figure B.25 note how rather unstructured flow patterns in the upper part of the catchment with subdued topography contrast with the more structured flows determined by the topography of the well-defined V-shaped valley in the lower part of the catchment.

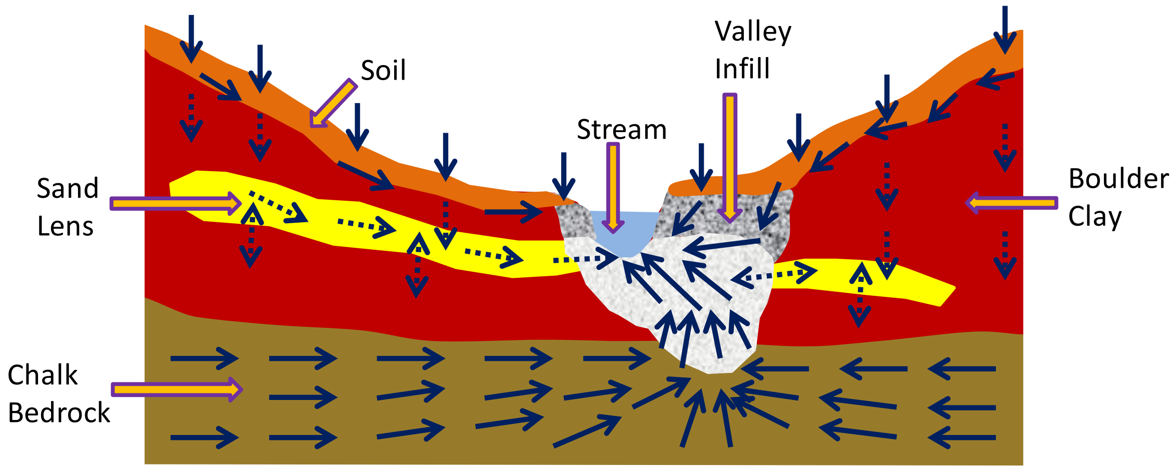


Figure B.26: Subsurface Water Flows in a Section of the Catchment

In Figure B.26, the main flows are shown as solid arrows and secondary flows are shown by broken arrows. Surface-water flows are not shown, as these are illustrated in Figure B.25. Regions where the flow direction is well defined are shown by single-headed arrows and regions where the flow direction is less well defined are shown by double headed arrows. Infiltration is expected to be strongly deflected at the interface between the soil and the boulder clay, leading to a downslope, interflow component. Deeper percolation into the boulder clay is restricted by its low hydraulic conductivity. Some of this deeper percolation is intercepted by the sand lens and is directed downslope. Flow in the chalk bedrock is shown as convergent to the high conductivity valley infill, but it is emphasised that this flow pattern is that relevant to the surface water catchment. Deeper in the chalk, the flow may be unidirectional, governed by the regional topography and lithostratigraphy rather than by local characteristics. The high hydraulic connectivity between the chalk and the valley infill dominates the pattern of up-flow, but because the chalk aquifer is confined, some limited up-flow into the boulder clay would occur, so mixing of aquifer water with recent meteoric water would occur within the boulder clay and sand lens.

Hydrogeochemistry

As illustrated in Figure B.26, the main water types that will be present comprise recent meteoric water derived from precipitation and upwelling water from the chalk aquifer. The meteoric water will be oxic, but it will become anoxic as it penetrates into the soil and underlying boulder clay. Indeed, it seems likely that the oxygen will be entirely consumed within the soil system. A typical rainfall composition for Eastern England is given in Table B.15.

Table B.15: Composition of Rainfall at Stoke Ferry, Norfolk [from Table 3.2 of Ander *et al*., 2004]

Parameter (annual mean value)	Rainfall composition	Rainfall composition x 3
pH	5.1	
Na (mg l^{-1})	1.26	3.79
K (mg l^{-1})	0.12	0.35
Ca (mg l^{-1})	0.78	2.34
Mg (mg l^{-1})	0.27	0.80
Cl (mg l^{-1})	2.20	6.59
SO_4 (mg l^{-1})	2.26	6.77
NO_3 (mg l^{-1})	2.48	7.44
NH_4 (mg l^{-1})	0.90	7.21
Total N (mg l^{-1})	1.26	3.78
SEC (µS cm^{-1})	27.2	81.80
Rainfall amount (mm)	435	

The water flowing in the chalk aquifer is also likely to be relatively recently derived from meteoric inputs. An illustrative composition is that of the Great Ouse Chalk Aquifer of Eastern England. This Cretaceous chalk aquifer has been identified as the most important aquifer in England (Ander *et al*., 2004). Its detailed characteristics are given in Table B.16.

Table B.16: Typical Composition of Chalk Groundwater [from Ander *et al*., 2004]

Parameter	units	min.	max.	median	mean	97.7th percentile	Upper baseline*	N
T	°C	10.5	13.1	11.5	11.6	13.1		46
pH		6.6	8.1	7.1	7.2	7.7		58
Eh	mV	227	449	423	402	449		40
DO	mg l^{-1}	0.32	10.0	6.2	5.5	9.8		43
SEC	µS cm^{-1}	469	1112	688	723	1082		77
δ^2H	‰	-54.9	-45.8	-51.0	-50.9	-46.8		38
δ^{18}O	‰	-8.0	-7.1	-7. 6	-7.5	-7.2		38
δ^{13}C	‰	-15.4	-12.2	-14.1	-14.0	-12.3		38
Ca	mg l^{-1}	81	188	128	130	183		77
Mg	mg l^{-1}	1.1	15	3.3	3.9	11		77
Na	mg l^{-1}	7.0	65	14	17	43		77
K	mg l^{-1}	0.41	15	2.7	3.2	8.3		77
Cl	mg l^{-1}	9.0	126	30	36	88		77
SO_4	mg l^{-1}	10	120	34	41	108		77
HCO_3	mg l^{-1}	190	398	277	283	371		77
NO_3 as N	mg l^{-1}	0.287	38.4	9.5	10.3	25.0	2-3	77
NO_2 as N	mg l^{-1}	<0.001	0.101	0.006	0.019	0.093		44
NH_4 as N	mg l^{-1}	<0.003	0.17	<0.003	0.011	0.088		77
P	mg l^{-1}	<0.1	0.20	<0.1	<0.1	<0.1		46
TOC	mg l^{-1}	0.4	5.6	1.3	1.6	4.9		76
DOC	mg l^{-1}	0.2	4.1	1.5	1.7	3.5		44
F	mg l^{-1}	0.10	0.58	0.17	0.20	0.53		47
Br	mg l^{-1}	<0.03	0.210	0.080	0.086	0.160		46
I	mg l^{-1}	0.002	0.034	0.005	0.006	0.012		44
Si	mg l^{-1}	4.5	13.3	7.4	8.0	13.0		46

* estimated upper baseline for elements modified by anthropogenic influences.

Concentrations may be enhanced above local baseline but less than regional upper baseline.

This water contains a substantial amount of dissolved oxygen and, consequently, exhibits a positive redox potential. The meteoric water that recharges this aquifer is slightly acidic (pH 5.1), so there is significant dissolution of the chalk resulting in high concentrations of calcium (about 130 mg L^{-1}) and bicarbonate (about 280 mg L^{-1}). As Ander *et al.* [2004] remark, the median value of pH (7.14) and small range are consistent with well-buffered groundwater controlled by carbonate equilibrium. The range of Eh values measured is small and consistently oxidising, with a median value of 423 mV. However, these data show poor quantitative agreement with the DO (dissolved oxygen) data, with which they would be expected to co-vary: this is due to the well-established difficulties in obtaining representative Eh measurements. The DO data show a greater range in the redox conditions than implied by the Eh values. Overall, the Great Ouse Chalk aquifer groundwaters are all of Ca-HCO_3 type, which is typical of unconfined Chalk groundwaters from other baseline studies [Ander *et al*., 2004]. Note that the aquifer in Figure B.26 is assumed to be confined within the local surface water catchment, but is taken to be unconfined at the larger regional scale and it is this larger scale that defines the local composition.

Thermal Regime

The depth of the section of interest is a few tens of metres. Over this depth range, the geothermal gradient would give rise to a temperature difference of < 1ºC. The main thermal distinction is that the annual temperature cycle at the surface is strongly attenuated within a few metres, such that nearly constant temperatures occur throughout the year at the depth of the regional aquifer (see Table B.16 where the aquifer temperature is similar to the mean annual temperature for Lowland Britain). Note that in State S1 the mean annual temperature would typically be a few degrees warmer than listed in Table B.16.

Perturbations due to Human Actions

In the context of the scenarios of interest, the main perturbation to be addressed is the sinking of a well for use in water abstraction. In State S1, the summer (May to August) moisture deficit is about 240 mm in Cr conditions (compared with about 180 mm in temperate, DO, conditions), but is much larger, at about 450 mm, in Cs conditions. Thus, whereas irrigation of crops may only be required in some years in DO and Cr conditions, it would be required in almost all years in Cs conditions, and irrigation of pasture (or fodder crops) may also be undertaken. Small-scale, garden irrigation may be achieved by wells constructed into perched water bodies present within the boulder clay, but inspection of Figure B.26 indicates that such water bodies would, in general, be less contaminated than the underlying regional aquifer. Furthermore, the limited sustainability of such perched water bodies could make it more appropriate to extract water from the regional aquifer even in the case of small-scale domestic and garden use. Thus, the appropriate perturbation is a pumped well extending a few metres to several tens of metres into the chalk aquifer and screened through the overlying boulder clay. The pumping rate for this well might be as low as a fraction of a cubic metre per day for a domestic well extending a few metres into the aquifer up to a few hundred cubic metres per day from a well extending several tens of metres into the aquifer with the abstracted water used for commercial agricultural purposes (see also Appendix A, Section A.8.1).

State S2

Climate

The climate of Lowland Britain is defined as conforming to DO of the Köppen-Trewartha scheme, as is observed in Central England at the present day. It is emphasised that all the present-day analogue stations representing this situation are located in Central England, so the range of climatic conditions across those stations is somewhat less than might be observed within the same area under the full range of global and regional climatic conditions that would result in a downscaled assignment of DO conditions to Lowland Britain.

Because the climate analogue stations are closely grouped spatially, the seasonal temperature cycle is very similar at all of them. Mean monthly temperatures exhibit a minimum of about 4ºC in January and February and a maximum of about 17ºC in July and August. Precipitation is fairly uniformly distributed throughout the year, though with a slightly increasing trend from February through spring and summer to reach a maximum in December and January. The decrease in mean monthly precipitation between January and February is typically about 30%. The annual mean precipitation is a little over 600 mm. Averaged over all DO analogue stations, there is only a very small annual moisture excess, but the individual stations range from deficits of around 100 mm to excesses of 200 mm. Summer moisture deficits are generally from 150 mm to 200 mm.

Topography and Lithostratigraphy

The topography and lithostratigraphy assumed at the present day are discussed above. For State S2, the same topography and lithostratigraphy are adopted, except that the main river channel is incised by an additional 8 m at its outlet from the catchment, with the degree of incision decreasing to zero at the origin of the main river, which is taken to be within the catchment. Minor stream channels joining the main river are additionally incised consistent with the main river channel where they join it and grade back to zero incision at their upslope origin.

Surface Water and Groundwater Flow Regime

The overall surface water and groundwater flow regime is expected to be very similar to that in State S1. The annual moisture excess in DO conditions is similar to that in Cr conditions. There is likely to be more variation in the quantitative characteristics of the surface and sub-surface flow regimes between the Cr and Cs conditions included under State S1 than between the Cr conditions defined under State S1 and the DO conditions defined for State S2.

Hydrogeochemistry

The likely groundwater types are similar to those described for State S1.

Thermal Regime

Similar to that described in State S1, but with the groundwater temperature around 11.5^{o}C, as in Table B.16.

Perturbations due to Human Actions

As summer moisture deficits are generally from 150 mm to 200 mm, irrigation of crops would be required in some years. Well characteristics would be similar to those in State S1.

State S3

Climate

The seasonal cycle at the EO climate analogue stations does not vary very much between stations. The main difference is in winter, with the mean temperature of the coldest month (January/February) ranging from 0^{o}C to -6^{o}C. The temperature of the warmest month (July) is around 10^{o}C to 11^{o}C. The mean annual temperature is typically about 3^{o}C. Precipitation is somewhat higher in winter than summer at most analogue stations, though one of the selected stations shows a different trend, with the mean monthly precipitation being lowest between January and May. Over all the selected stations, the precipitation is typically around 60 mm per month, but decreases to around 40 mm per month in April, May and June. The annual mean precipitation is just over 600 mm (almost identical to that in the DO conditions that prevail at the present day). Because the climate is cooler than at the present day, there is a small annual moisture excess of around 80 mm (compared with near zero under DO conditions). However, the smaller amounts of precipitation in early summer mean that the summer moisture deficit is almost identical to that at the present day (150 to 200 mm).

Topography and Lithostratigraphy

As for State S2.

Surface Water and Groundwater Flow Regime

The overall surface water and groundwater flow regime in spring, summer and autumn will be similar to that in States S1 and S2. However, winter temperatures are sufficiently low that most of the precipitation will fall as snow and surface water bodies will freeze to a significant depth. Thus, there is likely to be a significant spring melt effect with a peak in the discharge hydrograph in April/May. There will be some ground freezing in winter, but this will primarily be restricted to the topsoil layer and significant mechanical effects due to ground freezing are not expected to occur.

Hydrogeochemistry

The likely groundwater types are similar to those described for State S1.

Thermal Regime

Similar to that described in State S1, but with the groundwater temperature around 3^{o}C.

Perturbations due to Human Actions

As summer moisture deficits are generally 150 to 200 mm, irrigation of crops would be required in some years. Well characteristics would be similar to those in State S1.

State S4

Climate

The climate of State S4 is rather uncertain, because it depends on judgement as to the intensity of the associated global and regional climatic cooling. Under EC conditions, the mean temperature of the coldest month (January) ranges from -10^{o}C to -25^{o}C and the mean temperature of the warmest month (July) ranges from 10^{o}C to 18^{o}C. Under FT conditions, the mean temperature of the coldest month (February) ranges from -5^{o}C to -23^{o}C and the mean temperature of the warmest month (July or August) is 6^{o}C to 8^{o}C. The shift in coldest month to February under FT conditions should be given little weight, as it is difficult to select FT stations at latitudes and with west coast locations appropriate to a British context. Thus, overall, it seems reasonable to consider January to be the coldest month, with a mean temperature of -5^{o}C to -25^{o}C and July to be the warmest month, with a mean temperature of 6^{o}C to 18^{o}C. The difference in temperature between the coldest month and warmest month is strongly dependent on the analogue station selected and ranges from less than 15^{o}C for one FT station up to more than 35^{o}C for some EC stations. However, the largest seasonal ranges may reflect a greater degree of continentality at the analogue stations than would ever be experienced in the continental-marginal context of Britain. Overall, the mean annual temperatures at typical EC and FT stations is not very different (around -2^{o}C to -3^{o}C, respectively, with individual stations ranging from about 2^{o}C to -8^{o}C). In terms of precipitation, intra-annual trends for the FT analogue stations are very variable, with no clear seasonal distinctions. For EC analogue stations, there is generally a peak in precipitation in late summer to early autumn at around 60 to 100 mm per month and a minimum in January to March of around 10 to 30 mm per month, but some stations show little seasonal variation, with monthly values of around 80 mm throughout the year. The mean annual precipitation at FT and EC analogue stations is typically about 600 to 700 mm. The annual moisture excess is about 200 mm for EC analogue stations and about 400 mm for FT stations. The summer moisture deficit is typically about 100 mm for EC analogue stations and about 50 mm for FT stations, i.e. about 70 to 120 mm less than in present day, temperate conditions. Individual stations exhibit values ranging from a small summer moisture excess to a deficit of slightly more than 200 mm, with no clear distinction between the FT and EC analogue stations.

Topography and Lithostratigraphy

As for State S2.

Surface Water and Groundwater Flow Regime

With mean annual temperature of around -2^{o}C to -3^{o}C, but possibly ranging from 2^{o}C to -8^{o}C, and with a location beyond the margins of a British ice sheet, the site falls clearly within the periglacial environment, as defined by French [2007]. Specifically, French [2007] defines the periglacial domain as including all areas where the mean annual air temperature is less than 3^{o}C, which closely follows the limits proposed by Williams [1961] for solifluction and patterned ground. However, French [2007] further subdivides the periglacial domain at the -2^{o}C mean annual air temperature. Above that temperature, frost action occurs but does not necessarily dominate, whereas below that temperature frost action dominates. As frost action is identified as occurring in State S3 and the mean annual temperature of State S4 is typically around -2^{o}C to -3^{o}C, but could range down to -8^{o}C, it is here assumed that the mean annual temperature is sufficiently low for frost action to dominate.

At mean annual temperatures of -2^{o}C to -8^{o}C (a range over which frost action would be expected to dominate), permafrost is expected to be present. In this context, permafrost is defined as ground that remains at or below 0^{o}C for at least two consecutive years. Thus, the ground may be perennially, but not necessarily permanently, frozen. Also, because the freezing point of soil water may be depressed to several degrees below 0^{o}C, ground classified as being subject to permafrost may contain liquid soil water.

Permafrost is usually classified in terms of its extent as being continuous (90-100%), discontinuous (50-90%), sporadic (10-50%), or isolated (0-10%). Continuous permafrost generally requires mean annual air temperatures of below -8^{o}C [French, 2007], so it is not considered further here. In discontinuous permafrost terrain, bodies of frozen ground are separated by areas of unfrozen ground. As in the case of continuous permafrost, areas beneath river channels would be expected to comprise unfrozen ground. Where permafrost is sporadic or isolated, it is usually restricted to isolated ‘islands’ often occurring beneath peaty organic sediments.

It should be noted that State S4, is climatically less extreme than the climate that applied at the Last Glacial Maximum (MIS 2) at around 18,000 years BP. At that time, it is thought that continuous permafrost existed in Southern England [see Figure 11.6 of French, 2007].

Discontinuous permafrost can penetrate to considerable depths. At the present day, discontinuous permafrost is encountered in limited areas in northern Scandinavia, the Kola Peninsula, and the tundra and boreal forest areas between the White Sea and the Ural Mountains. East of the Urals, a broad zone of discontinuous permafrost exists across western and eastern Siberia. Here, the transition from discontinuous to continuous permafrost coincides approximately with the northern boundary of the boreal forest (taiga) and is accompanied by a sharp increase in the thickness of permafrost from around 25-30 m in the taiga to 300 m in the taiga-tundra transition zone and 400 m in the tundra [French, 2007]. However, it should be kept in mind that these areas of Siberia have been subject to low temperatures, but without ice cover, for an extended period in the Late Quaternary. In Lowland Britain, there is no evidence that permafrost has extended to depths of more than about 100 m [Harris, 2002].

Overall, for characterising State S4, it seems reasonable to assume permafrost depths of a few tens of metres below the interfluves, but with little permafrost in the valleys or below river channels. Conceptually, the situation is as illustrated in Figure B.27.

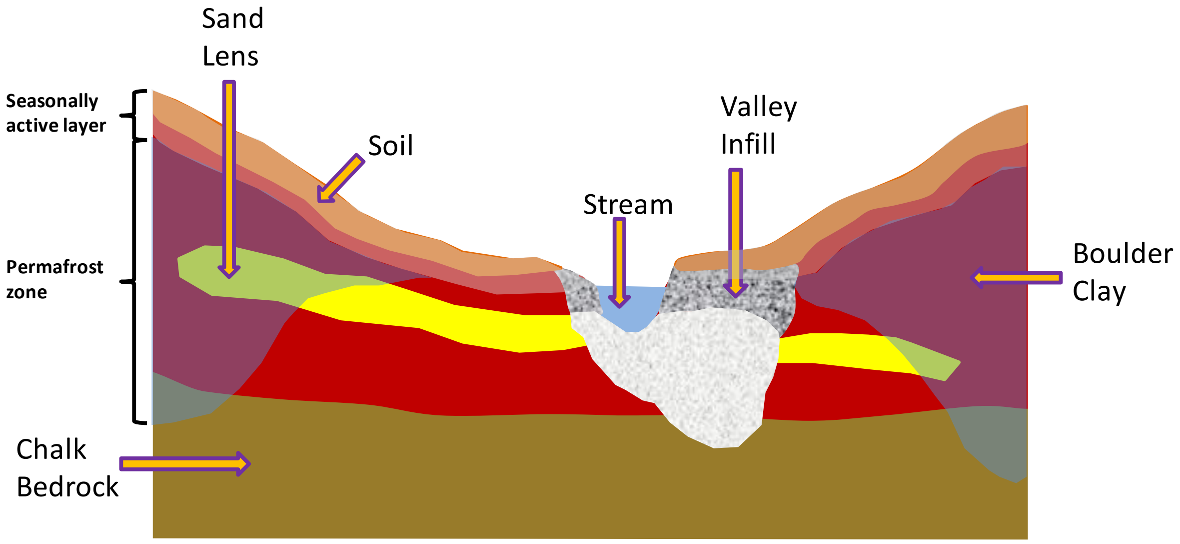


Figure B.27: Extent of Seasonally Frozen Ground (the seasonally active layer) and Discontinuous Permafrost

In this situation, groundwater recharge from infiltration will be restricted. However, groundwater recharge will enter a similar zone to that applicable in the warmer states, because permafrost does not develop in the high conductivity zone between the aquifer and the stream channel.

<u>Hydrogeochemistry</u>

The likely groundwater types are similar to those described for State S1. Because the permafrost is discontinuous, there are assumed to be areas of recharge and discharge of the aquifer present at the regional scale that lead to it remaining generally unconfined.

<u>Thermal Regime</u>

Surface temperatures are expected to be around -2ºC to -8ºC. If State S4 persisted for long enough, similar temperatures would be expected to penetrate to depths of 100 m or more. However, in practice, the duration of State S4 would be too short for this to occur. Therefore, it is more appropriate to consider temperatures grading from -2ºC to -8ºC at the surface to 0ºC at the base of the permafrost and 3ºC to 10ºC in the regional aquifer well below the permafrost, reflecting thermal conditions inherited from earlier climatic states plus a contribution from underlying geothermal heat production.

Perturbations due to Human Actions

As summer moisture deficits are generally small and agriculture is unlikely to be practiced in periglacial conditions, the primary well type is identified as one for domestic use with an abstraction rate that is likely to be a fraction of a cubic metre per day up to a few cubic metres per day, i.e. unlikely to be sufficient to significantly perturb the flow regime in the regional aquifer.

Spatial and Temporal Flux of Radionuclides

From Figures B.25 and B.26, it is clear that radionuclide fluxes will enter the GBI along the axis of the catchment, primarily through the valley infill. In addition, in States S1 to S3, radionuclides may be abstracted from wells drilled into the chalk bedrock with the abstracted fluxes directed to soil or to the central stream of the catchment (if the well is used for river augmentation to compensate for water extracted for various purposes further upstream or downstream). For the purpose of deriving biosphere dose conversion factors (BDCFs) as used by RWMD, it is appropriate to assume constant radionuclide concentrations in the unperturbed part of the chalk bedrock aquifer.

Outputs Required

For determining the applicability and values of BDCFs, it is necessary to estimate time-dependent radionuclide concentrations in soils, well waters and stream waters. The time taken for equilibrium (time-independent) concentrations to be approached in these media can be used to evaluate whether each state would persist for long enough for equilibrium BDCFs to be applicable. The values of the radionuclide concentrations in the various environmental media at or close to equilibrium can be used with supplementary data (e.g. plant:soil concentration ratios, animal product transfer factors, human habits data) to give BDCF values both for humans and for non-human biota.

Processes Operating within the Model and their Significance

In view of the similarity of the processes operating within the GBI in States S1 to S3, the process analysis is illustrated here only for State S1. This is then followed by a brief discussion of how this process description would be modified for State S4, but a full process analysis for State S4 is not undertaken.

Based on the above discussion, the following distinct components of the unperturbed GBI are identified.

a) Physical components:
- a1) Soils
- a2) Boulder Clay
- a3) Lenses and other layers of varying lateral extent comprising deposits of significantly higher hydraulic conductivity than the Boulder Clay, e.g. gravel, sand and silt, here described briefly as Sand lenses
- a4) Valley infill deposits
- a5) Chalk bedrock

b) Water bodies
- b1) Stream waters
- b2) Soil water
- b3) Groundwater in Boulder Clay
- b4) Groundwater in Sand lenses
- b5) Groundwater in Valley infill deposits
- b6) Chalk aquifer groundwater

c) Water types
- c1) Meteoric water
- c2) Aquifer water
- c3) Mixed water

Water bodies are defined to include both the flow characteristics and composition of those bodies. The composition is determined by the mixing of the various water types together with water-rock interactions with the physical components. Thus, there is a degree of overlap in the definitions of water bodies and water types. However, separating the two allows a natural distinction between aspects that are primarily addressed in hydrogeological studies from those addressed in hydrogeochemical studies.

Processes identified as operating between these components are illustrated in Figure B.28.

Soils					1,6	1,7	1,8		1,10				1,14
2,1	**Boulder Clay**					2,7	2,8	2,9	2,10	2,11			2,14
		Sand lenses			3,6		3,8	3,9	3,10				3,14
4,1			**Valley infill deposits**		4,6	4,7	4,8	4,9	4,10	4,11			4,14
				Chalk bedrock			5,8		5,10	5,11		5,13	5,14
6,1		6,3	6,4		**Stream waters**	6,7		6,9	6,10				6,14
7,1	7,2		7,4		7,6	**Soil water**	7,8		7,10				7,14
8,1	8,2	8,3	8,4	8,5		8,7	**Groundwater in Boulder Clay**	8,9	8,10	8,11			8,14
	9,2	9,3	9,4		9,6		9,8	**Groundwater in Sand lenses**	9,10				9,14
10,1	10,2	10,3	10,4	10,5	10,6	10,7	10,8	10,9	**Groundwater in Valley infill deposits**	10,11			10,14
	11,2		11,4	11,5			11,8		11,10	**Chalk aquifer**		11,13	11,14
12,1			12,4		12,6	12,7			12,10		**Meteoric water**		12,14
	13,2		13,4	13,5			13,8		13,10	13,11		**Aquifer water**	13,14
14,1	14,2	14,3	14,4	14,5	14,6	14,7	14,8	14,9	14,10	14,11			**Mixed water**

Figure B.28: Interaction Matrix for Components of the Geosphere-Biosphere Sub-system in States S1 to S3.

Some comments on the interaction matrix shown in Figure B.28 are required. First, the major components of the system are shown on the lead diagonal. Solids are coloured reddish-brown, water bodies blue and the chemical compositions of waters are shown in red. The geometry is that of Figures B.25 and B.26, so components that are not in direct contact do not affect each other. Thus, for example, **Groundwater in Boulder Clay** does not directly influence **Stream waters**, as **Valley infill deposits** lies between them. Here and throughout this discussion text in bold refers to the lead diagonal elements in Figure B.28.

Meteoric water and **Aquifer water** are end members supplied to the GBI from outside. This means that they are not influenced by any components of the GBI, but they can influence components of that sub-system. However, **Meteoric water** and **Aquifer water** are rapidly transformed to **Mixed water** as they penetrate the GBI. Thus, **Meteoric water** only interacts with materials exposed at the surface, i.e. **Soils**, **Valley infill deposits**, **Stream waters**, **Soil water** and **Groundwater in Valley infill deposits** (the **Valley infill deposits** are taken to be exposed at the stream banks). These are interactions 12,1; 12,4; 12,6; 12,7 and 12,10. Note that the interactions can be directly with solids, e.g. solution and precipitation, or with liquids, e.g. mixing. Similarly, **Aquifer water** interacts directly with **Boulder Clay**, **Valley infill deposits**, **Groundwater in Boulder Clay** and **Groundwater in Valley infill deposits** at the interface of the aquifer with these other media (13,2; 13,4; 13,8 and 13,10). **Aquifer water** also interacts with the **Chalk bedrock** and the **Chalk aquifer groundwater** within the aquifer (13,5 and 13,11). Indeed, it is these reactions together with the reverse reactions (5,13 and 11,13) that define the composition of **Aquifer water**, e.g. through precipitation/dissolution reactions in a flowing groundwater system.

A key role of **Meteoric water** and **Aquifer water** is the formation of **Mixed water** (12,14 and 13,14). However, the composition of **Mixed water** is altered throughout the system by direct interactions with solids (1,14; 2,14; 3,14; 4;14 and 5,14) and by interactions with the fluids included in those solids (6,14; 7,14; 8,14; 9,14; 10, 14; 11,14). This implies a complete set of reverse reactions (14,1 through to 14,11). The reactions include sorption/desorption, complexation, solution and dissolution at solid surfaces, and reactions between chemical species in solution. Colloid formation and dissolution are included.

The various solids condition the composition of their included waters (1,7; 2,8; 3,9; 4,10; 5,11) and *vice versa* (7,1; 8,2; 9,3; 10,4; 11,5). Note that **Aquifer water** is an end member and should not be confused with **Groundwater in the aquifer**. The latter is heterogeneous determined both by water mixing and water-rock interactions.

Water characteristics, including composition and flow field are determined by interactions across boundaries. Thus, **Soil water** influences the composition and flow of **Groundwater in Boulder Clay**, by flow across the boundary of the two media (7,8). Also, concentration differences across this boundary can lead to diffusional transport. Flow and transport can also occur in the opposite direction (8,7). Similar interactions across boundaries occur for other components of the sub-system (6,7; 7,6; 6,9; 9,6; 8,9; 9,8; 6,10; 10,6; 7,10; 10,7; 8,10; 10,8; 9,10; 10,9; 8,11; 11,8; 10,11; 11,10).

In addition to solids having an effect on their included waters, they can also affect the composition of waters in adjacent solids. It could be argued that this is mediated by flow and transport in waters across the interface, but it seems appropriate to recognise the complexities of such interfaces by allowing the possibility of a direct interaction (though, in practice, this is likely to be minor). Hence, interactions 1,6; 1,8; 1,10; 2,7; 2,9; 2,10; 2,11; 3,6; 3,8; 3,10; 4,6; 4,7; 4,8; 4,9; 5,8; 5,10 and 4,11 are included together with their reverse interactions of adjacent waters on the solids at the interface (6,1; 8,1; 10,1; 7,2; 9,2; 10,2; 11,2; 6,3; 8,3; 10,3; 6,4; 7,4; 8,4; 9, 4; 8,5; 10,5 and 11,4).

Finally, it is recognised that **Boulder Clay** and **Valley infill deposits** can evolve into **Soils** through the process of pedogenesis (2,1 and 4,1). This is of limited relevance in a time-invariant state, but would need to be addressed in a transition between states that was associated with erosion and incision, since pedogenesis would tend to regenerate the soil profile as superficial material was eroded.

In general terms, interactions at interfaces are likely to be of much less significance than flows across them or interactions within the bulk of the components. (It is of interest to note that this statement would be much more difficult to justify if flow and transport within a sparsely fractured system was under consideration.) This leads to the simplification of Figure B.28 shown in Figure B.29, where interactions of minor significance have been greyed out.

Soils					1,6	1,7	1,8		1,10				1,14
2,1	**Boulder Clay**					2,7	2,8	2,9	2,10	2,11			2,14
		Sand lenses			3,6		3,8	3,9	3,10				3,14
4,1			**Valley infill deposits**		4,6	4,7	4,8	4,9	4,10	4,11			4,14
				Chalk bedrock			5,8		5,10	5,11		5,13	5,14
6,1		6,3	6,4		**Stream waters**	6,7		6,9	6,10				6,14
7,1	7,2		7,4		7,6	**Soil water**	7,8		7,10				7,14
8,1	8,2	8,3	8,4	8,5		8,7	**Groundwater in Boulder Clay**	8,9	8,10	8,11			8,14
	9,2	9,3	9,4		9,6		9,8	**Groundwater in Sand lenses**	9,10				9,14
10,1	10,2	10,3	10,4	10,5	10,6	10,7	10,8	10,9	**Groundwater in Valley infill deposits**	10,11			10,14
	11,2		11,4	11,5			11,8		11,10	**Chalk aquifer groundwater**		11,13	11,14
12,1			12,4		12,6	12,7			12,10		**Meteoric water**		12,14
	13,2		13,4	13,5			13,8		13,10	13,11		**Aquifer water**	13,14
14,1	14,2	14,3	14,4	14,5	14,6	14,7	14,8	14,9	14,10	14,11			**Mixed water**

Figure B.29: Principal Interactions for Components of the Geosphere-Biosphere Sub-system in States S1 to S3.

In Figure B.29, the evolution of the sub-system through pedogenesis has been excluded from consideration, so the five physical components do not interact directly with each other. Instead they provide a setting in which they condition and are conditioned by their included groundwaters. Interactions between solids and groundwaters from adjacent components are neglected (i.e. interface effects are not considered to be important compared with interactions within components), so it is the flows of waters from one component to another that are the primary controls on both water composition and contaminant transport. The composition of meteoric water is not influenced by any component of the sub-system and the composition of aquifer water is influenced only by the nature of the chalk bedrock and the flow system of the chalk aquifer groundwater.

When perturbations by wells are included, the above system has to be extended to include the well as a physical component and abstracted well water as a water body. In principle, these two components interact with all the other components. However, with a well that abstracts water only from the chalk aquifer, with that water used for irrigation, the key aspects of the interaction matrix are as shown in Figure B.30.

Soils			1,4					1,9
	Well			2,5	2,6			2,9
		Chalk bedrock		3,5	3,6		3,8	3,9
4,1			Soil water					4,9
5,1	5,2		5,4	Abstracted well water	5,6			5,9
	6,2	6,3		6,5	Chalk aquifer groundwater		6,8	6,9
7,1			7,4			Meteoric water		7,9
		8,3			8,6		Aquifer water	8,9
9,1	9,2	9,3	9,4	9,5	9,6			Mixed water

Figure B.30: Supplementary Interaction Matrix for Inclusion of a Well in the Geosphere-Biosphere Sub-system in States S1 to S3

The structure shown in Figure B.30 carries over various aspects of Figures B.28 and B.29. The physical components are considered to provide a setting for the conditioning of groundwaters. **Soil** conditions **Soil water** and is conditioned by it (1,4 and 4,1). Similarly, the **Well** conditions the **Abstracted well water** and is conditioned by it, e.g. by corrosion of well components (2,5 and 5,2). The **Chalk bedrock** conditions the characteristics of the **Chalk aquifer groundwater** and is conditioned by it (3,6 and 6,3), but the **Chalk aquifer groundwater** is also determined by the composition of the **Aquifer water** end member (8,6). It is debatable whether the influence of the **Chalk aquifer groundwater** on the **Aquifer water** end member should be included (6,8), but this has been done to provide a reminder that it may not be possible to define this end member sufficiently far from the GBI for it to be unperturbed by that system. Furthermore, the **Aquifer water** composition is determined by the physical and chemical nature of the **Chalk bedrock** (3,8), but also determines that physical and chemical nature, e.g. through dissolution reactions (8,3). Both **Meteoric water** and **Abstracted well water** interact directly with **Soils** (7,1 and 5,1) and also mix and react with **Soil water** (7,4 and 5,4). The **Chalk aquifer groundwater** interacts directly with the **Well**, e.g. through corrosion reactions and the precipitation of solids (6,2) and is a major determinant of the characteristics of **Abstracted well water** (6,5). Similarly, the flow and chemical composition of the **Abstracted well water** influence the **Chalk aquifer groundwater** (5,6) and the structure of the **Well** may influence the **Chalk aquifer groundwater**, e.g. by providing a path by which oxygen, nutrients and pollutants may penetrate to depth (2,6). Mixing of the end member waters occurs throughout the system and the composition of **Mixed waters** is determined by the nature of the end members (7,9 and 8,9), the mixing regimes (4,9; 5,9 and 6,9) and interactions with solids (1,9; 2,9 and 3,9). In turn, these mixed waters affect the properties of sub-system solids (9,1; 9,2 and 9,3) and the properties of their associated waters (9,4; 9,5 and 9,6).

Finally, some remarks are appropriate relating to State S4. In this case, the solid media can be distinguished into unfrozen, seasonally frozen and perennially frozen components. Thus, the set of components might be as set out in Table B.17.

Table B.17: Possible Set of Components for State S4 (see also Figure B.27)

Physical Components	Water Bodies	Water Compositions
Seasonally frozen soil	Liquid water in streams	Meteoric
Seasonally frozen Boulder Clay	Ice in streams	Aquifer
Perennially frozen Boulder Clay	Liquid water in soil	Mixed
Unfrozen Boulder Clay	Ice in soil	
Perennially frozen sand lenses	Liquid water in Boulder Clay	
Unfrozen sand lenses	Ice in Boulder Clay	
Seasonally frozen valley infill deposits	Liquid water in sand lenses	
Perennially frozen valley infill deposits	Ice in sand lenses	
Unfrozen valley infill deposits	Liquid water in valley infill deposits	
Perennially frozen chalk bedrock	Ice in valley infill deposits	
Unfrozen chalk bedrock	Liquid water in chalk bedrock	
	Ice in chalk bedrock	

An interaction matrix for State S4 is not developed here. In addition to flows of water between the various physical components, it will be necessary to consider the effects of freezing and thawing on the chemical composition of the various water bodies and the influence of the chemical composition of those water bodies on their susceptibility for freezing and thawing.

Coupling between Components

Coupling between components is evaluated for the principal components shown in Figure B.29. These couplings can be distinguished into a limited number of categories. This is illustrated in Table B.18, which also sets out the processes that would result in these couplings.

Table B.18: Processes determining the Couplings shown in Figure B.29

Interactions (Numbered as in Figure 4.23)	Description of the Interactions	Relevant Processes
1,7; 7,1; 2,8; 8,2; 3,9; 9,3; 4,10; 10,4; 5,11; 11,5	Interactions between a solid and its included water	Sorption/desorption; precipitation/dissolution; colloid formation and dissolution; advective and dispersive transport within the solid, including diffusion into intra-particle and inter-particle pore spaces. Relevant both to the composition of the solid and its included water and to the transport of contaminants within the solid/water system.
1,14; 2,14; 3,14; 4,14; 5,14	Effects of a solid on the composition of waters formed by the mixing of meteoric and aquifer waters	Rock-water interactions that modify the chemical composition of waters with different degrees of mixing. Mainly relevant to defining the composition of waters within which contaminant transport occurs.
5,13; 13,5	Interactions between the chalk aquifer and its included groundwater outside and within the GBI that together define the aquifer end-member water that is involved in the mixing process.	Rock water interactions throughout the aquifer, taking into account the composition of the meteoric water that recharges the aquifer at outcrop. Mainly relevant to defining the composition of waters within which contaminant transport occurs.
6,7; 7,6	Exchange of water between flowing streams and soils	Recharge and discharge through the stream banks and bed. Overbank flooding and return flow. Mainly relevant to contaminant transport.
6,9; 9,6	Exchange of water between flowing streams and sand lenses where the latter outcrop in the stream bed or banks.	Recharge and discharge through the stream banks and bed. Overbank flooding and return flow. Mainly relevant to contaminant transport.
6,10; 10,6	Exchange of water between flowing streams and groundwater in valley infill deposits where the latter outcrop in the stream bed or banks.	Recharge and discharge through the stream banks and bed. Overbank flooding and return flow. Mainly relevant to contaminant transport.
6,14; 7,14; 8,14; 9,14; 10,14; 11,14	Mixing of stream waters or groundwaters of various types with pre-existing mixed waters to modify the composition of those mixed waters.	Chemical reactions between waters of differing composition leading to changes in chemical speciation and the formation/dissolution of colloids. Mainly relevant to defining the composition of waters within which contaminant transport occurs.
12,14; 13,14	Mixing of incoming meteoric water or aquifer water with existing mixed waters to modify the composition of those mixed waters.	Chemical reactions between waters of differing composition leading to changes in chemical speciation and the formation/dissolution of colloids. Mainly relevant to defining the composition of waters within which contaminant transport occurs.

Table B.18: Processes determining the Couplings shown in Figure B.29 (Continued)

Interactions (Numbered as in Figure 4.23)	Description of the Interactions	Relevant Processes
7,8; 7,10; 8,7; 8,9; 8,10; 8,11; 9,8; 9,10; 10,7; 10,8; 10,9; 10,11; 11,8; 11,10	Flow of water across interfaces between different media	Advective flow of water in both unsaturated and saturated conditions. Relevant to bringing different waters into contact for mixing processes and for the transport of contaminants.
11,13; 13,11	Interactions of the aquifer end-member water within the aquifer zone of the GBI to give modified aquifer water composition. These interactions are shown as bidirectional because it may not be possible to define the completely unperturbed aquifer end-member water.	Chemical reactions between waters of differing composition leading to changes in chemical speciation and the formation/dissolution of colloids. Mainly relevant to defining the composition of waters within which contaminant transport occurs.
12,1; 12,4	Interactions of meteoric waters with soils and valley infill deposits at outcrop leading to direct modification of the solids.	Chemical reactions between meteoric waters and solids leading to weathering of those solids with changes in composition and structure.
12,6; 12,7; 12,10	Interactions of meteoric waters with surface waters and groundwaters.	Inputs of meteoric water affect the flow regime and also give rise to chemical reactions between waters of differing composition leading to changes in chemical speciation and the formation/dissolution of colloids. Relevant both to defining the flow regime and the composition of waters in which contaminant transport occurs.
14,1; 14,2; 14,3; 14,4; 14,5	Effects of mixed waters of various compositions on the structure and properties of solids.	Sorption/desorption; precipitation/dissolution; colloid formation and dissolution.
14,6; 14,7; 14,8; 14,9; 14,10; 14,11	Effects of mixed waters of various compositions on the composition of surface waters and pore waters in various solids.	Chemical reactions between waters of differing composition leading to changes in chemical speciation and the formation/dissolution of colloids. Mainly relevant to defining the composition of waters within which contaminant transport occurs.

B.3.3 Central Spain

As most of the issues relevant to developing conceptual models of the GBI have been illustrated in Sections B.3.1 and B.3.2, only a brief account of some key points of importance is provided for Central Spain. The assessment context is as set out in BIOCLIM [2004] and the scenario described in Appendix C3 of BIOCLIM [2004] is taken as a basis for analysis.

The landscape and climatological context is set out in Section B.2.3. The area of interest includes both upland and lowland, with subdued landforms intersected by fluvially incised valleys. Surface water bodies are mainly flowing rivers, with some reservoirs located on the main rivers. The river valley system around Aranjuez is shown for illustration in Figure B.31. This is within the area centred on Toledo that was considered in BIOCLIM [2004] and includes the Tagus valley that was given particular attention within that area.

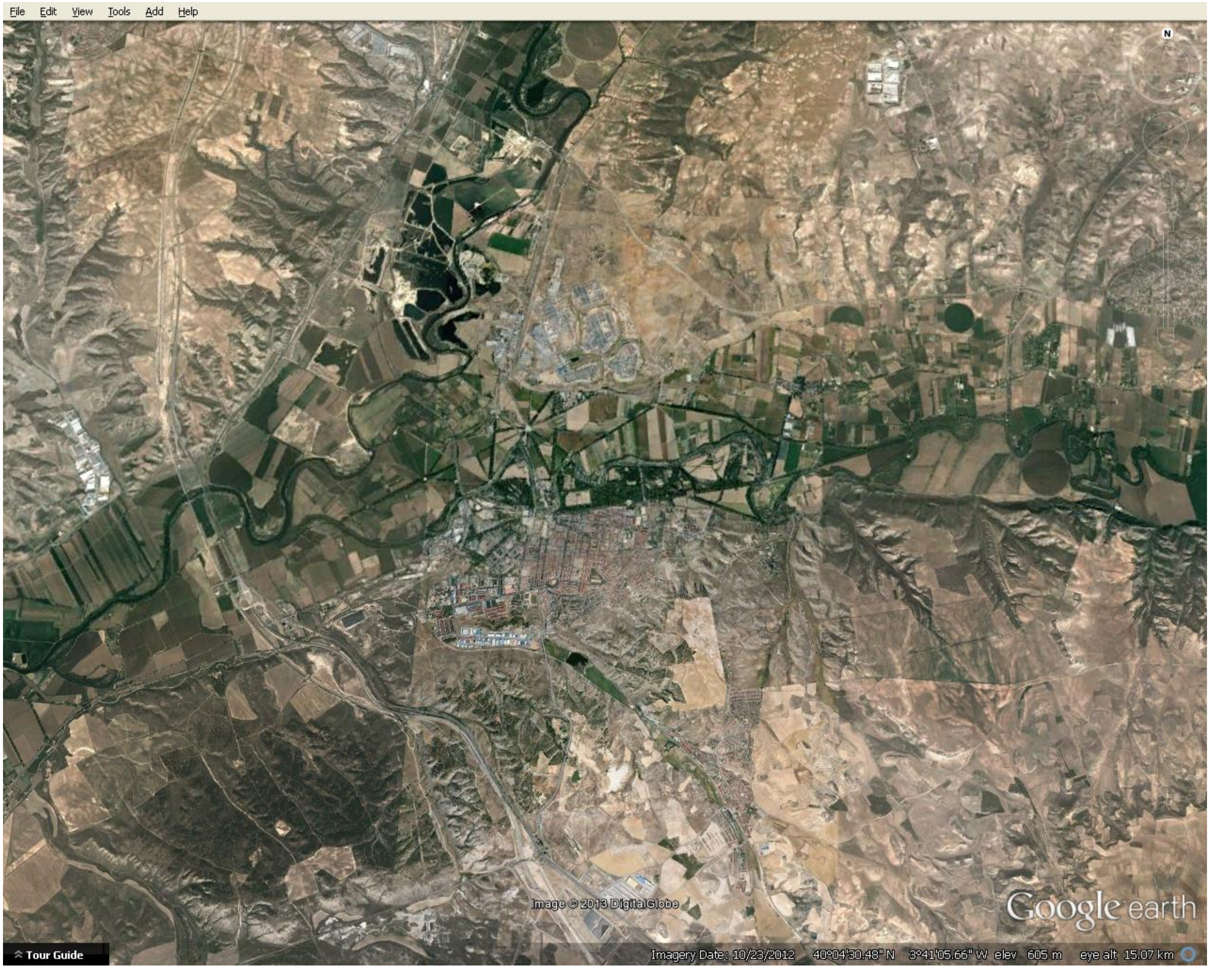


Figure B.31: Tagus River Valley System in the Vicinity of Aranjuez.

As discussed in Section B.2.3, the sequence of states and transitions set out in Table B.19 is expected to occur out to 175 ka AP under a scenario in which a significant amount of anthropogenically induced greenhouse-gas warming occurs. It is this sequence of states and transitions that is adopted for illustrative purposes here. Note that the initial 300 year transition from the current climate to a much warmer (BWh) regime is omitted, since this period is too short to be of much relevance in the context of deep geological disposal.

Table B.19: Sequence of Climate States and Transitions adopted for Central Spain.

State or Transition	Köppen-Trewartha Climate	Duration (ka)	Period (ka AP)
S1	BWh	2	0 - 2
T1	BWh to BSh	3	2 - 5
S2	BSh	75	5 - 80
T2	BSh to CSb	20	80- 100
S3	CSb	16	90 - 106
T3	Oscillations through BSh and CSb	52	106 - 158
T4	BSh to DC or BWk/BSk	17	175

Although a very warm climate (mean annual temperature 32°C dropping to about 27°C) is expected to persist over the next 5 ka, for a deep repository this is of limited interest, as significant releases of radionuclides would not be expected on this timescale. Thus, attention is concentrated here on the subsequent 75 ka period (state S2). This is classified as BSh and has a mean annual temperature of 19°C to 22°C, i.e. about 6°C higher than the current mean annual temperature of 13°C to 17°C.

The characteristics of the GBI during state S2 are taken from BIOCLIM [2004] and are listed in Table B.20.

Table B.20: Description of State S2 of the Geosphere-Biosphere Sub-system for the Tagus Valley, Central Spain

Component	Description
Climate	Semiarid with a mean annual temperature of about 21°C. The mean annual precipitation from seven analogue meteorological stations was 521 mm, but the range was between 144 mm and 879 mm.
Atmosphere	Similar to the present day.
Topography	River valley with alluvial deposits.
Near-surface lithostratigraphy	The soils are mainly cambisols, lithosols and fluvisols. These overly a complex sequence of alluvial deposits. The Quaternary began with the deposition of piedmont deposits, followed by fluvial dissection that created a complex system of terraces, glacis and alluvial fans. Piedmont deposits and river terraces are the typical deposits of the Tagus River.
Water bodies	Rivers and secondary streams. Springs. Reservoirs. A variably saturated zone overlying a regional water table that can be located at significant depth.
Biota	The natural vegetation would comprise Mediterranean pine forest and grassland. However, extensive arable agriculture and animal husbandry can be undertaken given adequate water availability.

Overall, the situation is not very different from that illustrated for Lowland Britain in Figures B.25 and B.26, with a river channel incised into a mixed unconsolidated sedimentary sequence and with the potential for the construction of wells for both domestic and commercial agricultural purposes.

Therefore, this GBI has not been subject to further analysis, since the overall structure of the conceptual model would be similar to that developed for Lowland Britain, though with an underlying rock type other than chalk.

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