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Components, features, processes and interactions in the biosphere

Svensk Kärnbränslehantering AB

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Contents

1 Introduction

This report describes processes and interactions between components in the biosphere that may be important in a safety assessment for radioactive waste disposal in the Forsmark area. This report is an updated version of the earlier biosphere process definition report (SKB 2010a). Since then, the Interaction Matrix (IM) describing components of the biosphere and interactions between those components has been updated to more clearly visualise the physical components; and the influence of features on physical components and processes are described. The biosphere processes are general, i.e. they can be used in all safety assessments for underground repositories and are not specific to a particular method or location. Processes related to the geosphere and specific repository types (e.g. the KBS-3 method) can be found in Skagius et al. (1995) and SKB (2001, 2006, 2010b). This report describes a biosphere IM that has been used in the safety assessment SR-PSU (SKB 2014c) and that can be used in future safety assessments at the Forsmark area. The work of defining and characterising processes in the biosphere is ongoing and many persons from different disciplines have been involved in the identification and characterisation of those processes (see Table 1-1).

1.1 Background

In a safety assessment for the biosphere, it is necessary to understand how ecosystems function to be able to predict pathways and sinks of radionuclides in the ecosystem and, primarily, doses to humans and other biota.

One way to systematically identify important processes is to construct an IM (Hudson 1992). In an IM, the system (in this case an ecosystem) is divided into separate components, and interactions (processes) between the components are identified. After identifying interactions between different components in an ecosystem, their importance for determining radiation doses to humans and other biota can be assessed. This may be done for various ecosystems and may differ depending on the type of repository and the radionuclides of relevance. In addition to being used as a tool in defining radionuclide transport models, the IM may also be used in the planning of site investigations and ecosystem modelling, with the aim of identifying important processes for radionuclide transport and accumulation. Site investigations, ecosystem models, and radionuclide transport models, along with other scientific research, are the most important sources for improving our understanding of ecosystem function and radionuclide behaviour. These sources may also generate information that can be used to update and improve the IM (Figure 1-1).

SKB has been working with IMs to describe the effects of deep repositories since the early 1990s (Eng et al. 1994, Skagius et al. 1995, Pers et al. 1999), and earlier versions of interaction matrices for the biosphere were described in 2001 and 2010 (Kautsky 2001, SKB 2001, 2010a). In parallel with SKB's works, others also produced IMs for ecosystems, e.g. Avila and Moberg (1999), Velasco et al. (2006) and Posiva (2012, 2013). However, with the exception of Posiva (2012, 2013), these IMs do not always provide a representation of the processes involved, but are rather to be viewed as transfer matrices illustrating transfer parameters between different components of the system.

NEA has produced a database of Features, Events, and Processes (FEPs) that is used in safety assessments of repositories for radioactive waste by a number of countries. According to NEA (2000) *"A FEP is a feature, event or process or other factor, that may be necessary to consider in a repository safety assessment. This includes physical features, events and processes that could directly or indirectly influence the release and transport of radionuclides from the repository or subsequent radiation exposure to humans, plus other factors, e.g. regulatory requirements or modelling issues that constrains or focus the analysis".*

SKB has set up FEP catalouges in a SKB FEP database based on Interaction Matrices developed for SFR 1 in early safety assessments of the SFR repository. FEP catalouges have been developed throughout safety assessments for SFR and a planned repository for spent nuclear fuel. The latest FEP processing work for SFR (in the safety assessment SR-PSU) included audits against the Project FEPs in version 2.1 of the NEA international FEP database and against additional FEP lists from two low- and intermediate level waste projects, as well as the involvement of experts from different disciplines (SKB 2014b).

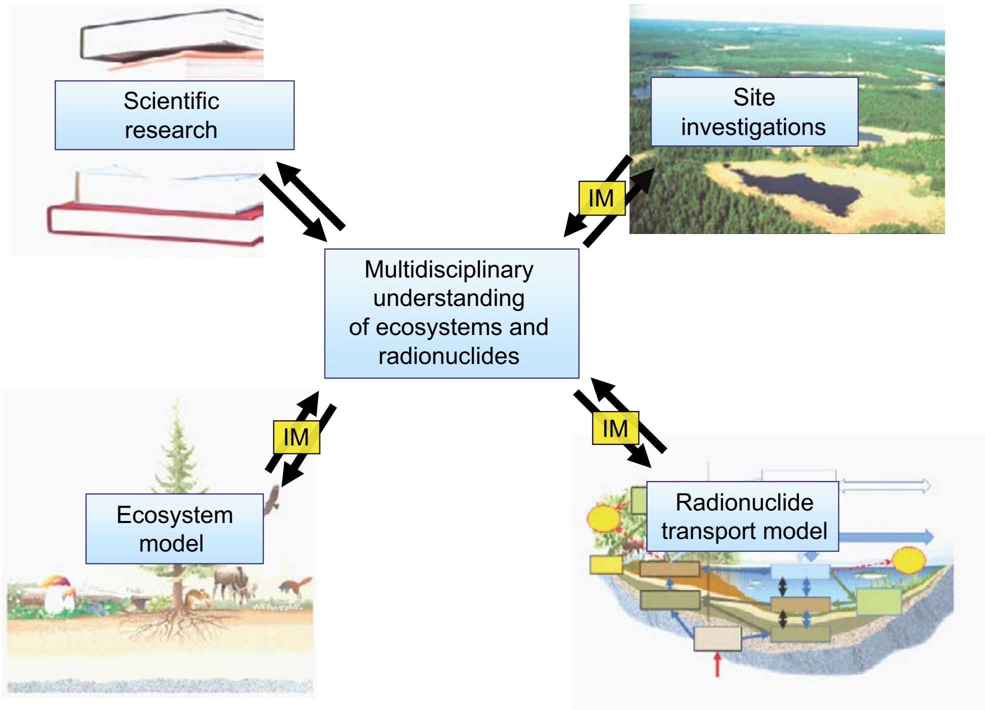

Figure 1-1. *A general understanding of the system in question is vital when setting up radionuclide transport models in a safety assessment. Scientific research, site investigations and ecosystem models may be used to improve this understanding, and interaction matrices may be used as a tool to ensure a systematic approach when setting up models and investigation plans in order to ensure that all important process interactions are included. Radionuclide transport models may in turn further improve a general understanding of radionuclide behaviour in the environment and be used to improve the interaction matrices.*

Since the initial biosphere IM was produced, site investigations have been carried out in Forsmark and Laxemar-Simpevarp in Sweden, and comprehensive ecosystem understanding for these sites has been reported in three ecosystem reports (Andersson 2010, Aquilonius 2010, Löfgren 2010) and ecosystem models based on data from the site investigations have further improved our understanding of ecosystem function. As a result, SKB has improved the biosphere IM. Since the 2010 version, the IM has been updated to more clearly visualise the physical components and how features influence both physical components and processes, and description of processes interactions has been extended.

Table 1-1. Persons who have participated in the development and improvements of the biosphere interaction matrix. The biosphere interaction matrix was first presented in 2001 and an updated version was presented in 2010. Since then, the interaction matrix has been even further developed to more clearly visualise the process interactions between physical component. Reviewers have contributed substantially to the development of the IM, and we would especially like to thank Mike Thorne at Mike Thorne Ltd.

Person	Expertise	Participated in the development of the previous biosphere interaction matrices (prevIM) or the biosphere interaction matrix developed in 2013 and described in this report (BiosphereIM2013)
Ulrik Kautsky SKB	Project manager for the work with the interaction matrix and process definitions for the biosphere, Systems ecology, Radioecology, Safety assessments	prevIM and BiosphereIM2013
Eva Andersson SKB	Editor of this report, Limnology	prevIM and BiosphereIM2013
Karin Aquilonius Studsvik Nuclear AB	Co-editor of this report, Marine biology	prevIM and BiosphereIM2013
Sten Berglund HydroResearch	Hydrology and transport	BiosphereIM2013
Ulla Bergström Studsvik Ecosafe AB	Radiochemistry	prevIM
Lars Brydsten Umeå University	Physical geography	prevIM
Anders Engqvist A&I Engqvist consult AB	Oceanography	prevIM
Sara Grolander	Co-editor of this report	BiosphereIM2013
Thomas Hjerpe Facilia	Radiation protection, Safety assessment	BiosphereIM2013
Martin Isaeus Stockholm University	Botany	prevIM
Linda Kumblad Stockholm University	Systems ecology	prevIM
Tobias Lindborg SKB	Terrestrial ecology, Safety assessment	prevIM
Angelica Lorentzon SKB	Systems ecology	prevIM
Anders Löfgren EcoAnalytica	Terrestrial ecology	prevIM and BiosphereIM2013
Marcus Meili Uppsala University	Limnology	prevIM
Sara Nordén	Ecology	BiosphereIM2013
Peter Saetre	Ecology, Model developments	BiosphereIM2013
Kristina Skagius SKB AB	Migration processes, Safety assessment	prevIM
Björn Söderbäck SKB	Limnology	prevIM
Marie Wiborgh Kemakta Konsult AB	Chemistry, Safety assessment	prevIM

2 This report

This chapter presents the aims of this report and serves as a guide to the reader by describing how the different chapters are related. The report was produced within the SR-PSU but is general and can be used also in future safety assessments. For the specific handling of Biosphere FEPs in SR-PSU, the reader is referred to SKB (2014c).

2.1 Aims

The general aims with this report are to:

1. Present definitions of the physical components, processes and features in the biosphere.
2. Identify interactions between different physical components in the biosphere system that are important for the transport and accumulation of radionuclides.
3. Describe the processes underlying the interactions and how different features may influence the occurrence/rate of the process.

2.2 Overview of contents

This report includes a set of definitions and descriptions of biosphere components and processes. The definitions are generally accepted in the scientific community and, where appropriate, references are given to the sources of the definitions. However, since the processes are complex and alternative definitions are sometimes found in the literature, and since some processes are lumped together, the process names and definitions set out herein may differ somewhat from those used by other authors. This document describes how SKB uses and the interprets the named processes and how it defines the different components of the biosphere. These descriptions can, in some cases, be broader or narrower than those used by other authors.

Chapter 1 includes an introduction and gives a background and history of SKB's work with interaction matrices and FEPs.

Chapter 2, this chapter is a reader's guide.

Chapter 3 describes the concept of IMs and the methodology used in their development.

Chapter 4 gives the SKB definition of physical components of the biosphere. A physical component of the biosphere is a part of the biosphere that can be physically distinguished from other parts (e.g. primary producers, regolith or surface waters).

Chapter 5 describes the features (variables) that affects the occurrence, rate, and direction of processes (e.g. geometry, temperature) in the biosphere.

Chapter 6 describes the processes in the biosphere that are relevant to safety assessment. A process is an interaction between ecosystem components affecting ecosystem functions, landscape development, transfer and accumulation of radionuclides in the ecosystems present, or radiation exposure of humans and other biota.

Chapter 7 describes the general IM for the biosphere and give a comprehensive description of process interactions between the physical components in the biosphere.

Chapter 8 is a concluding chapter with identification of which processes are important to consider for the biosphere in a safety assessment.

Appendix A Figure of the Interaction matrix with possible process interactions in the biosphere.

Appendix B Figure over the Interaction matrix where biosphere processes identified as needed to be considered in a safety assessment are shown.

Appendix C consists of tables describing the influence of features (variables) on processes and vice versa.

Appendix D is a list of synonyms and names of sub-processes commonly used in the literature and references indicating which process they are associated with in the biosphere IM.

3 Concept, boundaries and methodology behind the development of the interaction matrix

In a safety assessment it is necessary to identify all factors that are important for the transport and accumulation of the contaminants. The biosphere includes a large number of processes and complex interactions that do not significantly influence the transport and accumulation of radionuclides in the environment, and are thus not important to include in a radionuclide transport and impact model. A systematic approach is needed to identify and include all the important processes affecting transport and accumulation of radionuclides in the biosphere, while excluding those processes that are not important in this context. A broad approach has been applied in the development of the IM, and site investigations, literature research and modelling have been used to set up both the IM and radionuclide transport models. A comprehensive description of ecosystem functioning in Forsmark and Laxemar-Simpevarp serves as a basis in the safety assessments undertaken by SKB and the ecosystems are described in the three ecosystem reports; Terrestrial Ecosystems (Löfgren 2010), Limnic ecosystems (Andersson 2010) and Marine ecosystems (Aquilonius 2010). Both biological processes (e.g. primary production, respiration), and abiotic processes (e.g. precipitation, runoff, weathering) are important for the transport of radionuclides, and knowledge from several disciplines is needed to produce a comprehensive IM. The development of the IM, therefore, involved experts from different disciplines in a series of documented meetings. SKB produced an initial IM for the biosphere in the SAFE project, and an up-dated IM in SR-Site, with the aid of experts from several disciplines (Table 1-1 and SKB 2001, 2010a). The present IM has since been further refined by experts at several meetings. Therefore this work is seen as an iterative process of including new findings and remedying shortcomings in the IM.

The general principles of an interaction matrix (IM) are illustrated in Figure 3-1. The IM comprises major elements; the diagonal elements representing the physical components of the system in question, e.g. an ecosystem, the interactions describing the processes between the components and the features (variables) i.e. properties or conditions affecting the rate or direction of the processes between components.

3.1 Conceptual system definition

The (system) boundaries delineate the biosphere system. The biosphere is commonly defined as the region of the Earth and its atmosphere in which life exists (Vernadsky 1998, Porteous 2000). In the terminology of SKB, the biosphere is usually defined as the region above the rock surface, and may, therefore, more appropriately be referred to as surface ecosystems. The boundaries are the geosphere, the outer atmosphere and all conditions and processes taking place in the surrounding environment having an impact on the biosphere system.

It is sometimes difficult to make a clear distinction between biosphere and geosphere and some sets of processes e.g. those relating to hydrology and near-surface hydrogeology interact across the interface of the geosphere and the biosphere. The biosphere includes regolith, hydrological and subsurface hydrogeological systems, biota (including humans), and the overlying atmosphere (Figure 3-2).

The surface is often divided into distinct ecosystems distinguished by the importance of certain common processes. An ecosystem comprises biota – e.g. plants, animals and microbes – that live in a defined zone and their physical environment (Porteous 2000). Examples of ecosystems are lakes, seas, mires, agricultural land, and forests. The IM concerns all these ecosystems present at the region of Forsmark today and those potentially found under the expected climate condition during the forthcoming interglacials (SKB 2014a). The IM may be applied to these different ecosystems separately and some processes may thereby become more or less important to the transport and accumulation of radionuclides in specific ecosystems. Therefore, the resulting IM is applicable to a broad range of ecosystems.

Humans are included in the IM as a diagonal element (see below) and are represented under historical and present day technical and socioeconomic conditions in regard to the use of natural resources.

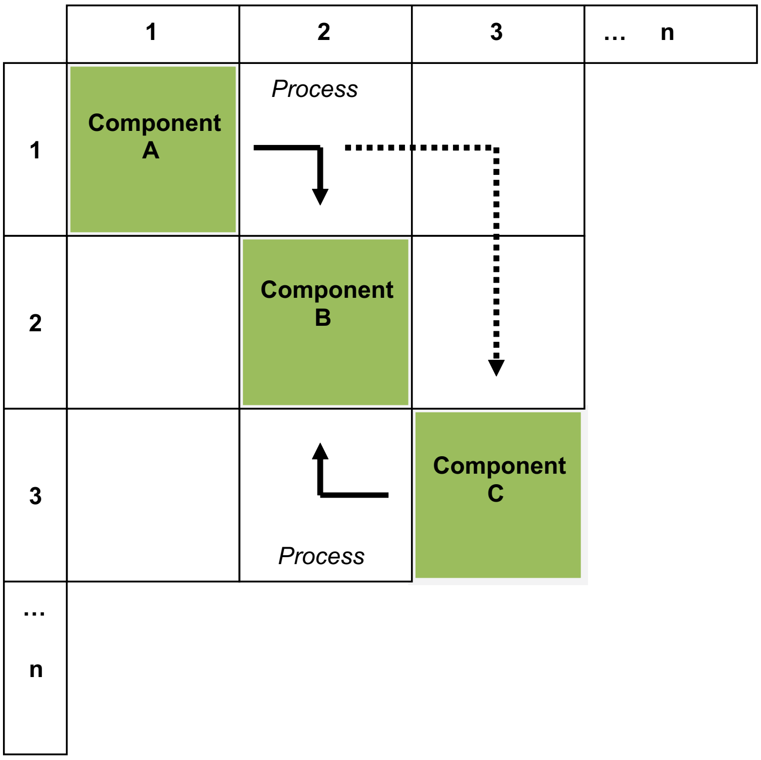

Figure 3-1. *Conceptual illustration of an interaction matrix. The diagonal elements A, B and C are key components of the system, i.e. biosphere components, and are placed on the diagonal. The off-diagonal elements (white boxes) represent one or more processes. The arrows illustrate e.g. how Component A (1:1) affects Component B (2:2) via a process (1:2). The matrix is always read clockwise, i.e. so that processes by which component A affects component C are found in the top right element, whereas processes by which component C affects component A are found in the bottom left element. Coordinates are read (row:column). An element can be empty if there is no process that allows the source lead-diagonal element to affect the target lead-diagonal element.*

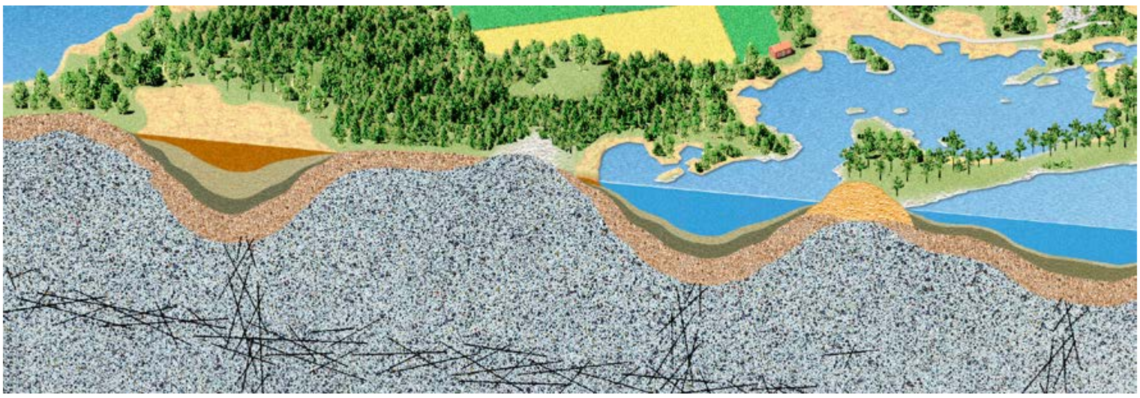

Figure 3-2. *The biosphere includes regolith, hydrological and subsurface hydrogeological systems, biota (including humans), and the overlying atmosphere.*

3.2 Biosphere components and processes

When developing an IM the major biosphere components of the system are listed along the lead diagonal of the matrix. The division into different components was done by experts from several fields of expertise (Table 1-1). Due to the complexity of ecosystems, different authors sometimes subdivide the biosphere differently than done here. The definitions in this report should therefore be regarded as those of SKB and may differ somewhat from other definitions in the literature. The biosphere components are spatially or conceptually distinct. Thus, for example, two components might be water in regolith and local atmosphere (physically distinct) or herbivores and carnivores (conceptually distinct). It is worth noting that, in general, different types of biota are distinguished by ecosystem function. Thus, omnivores do not appear in the interaction matrix because functionally they are a mix of herbivores and carnivores.

The number of diagonal elements is a measure of matrix resolution. If the number of leading diagonal elements increases, then the number of possible interaction terms and the matrix resolution also increase. The number of elements is often a compromise between the need to keep the matrix to a manageable size and the requirement to be as specific as possible in defining the processes relating the various components of a system. To keep the number of diagonal elements manageable there are often processes acting within diagonal elements. However, to make the IM more useful for pathway analysis, the diagonal elements should be selected in such a way that as many binary interactions as possible are placed in off-diagonal elements. As an example, distinguishing biota into different species would result in an unmanageably large IM, whereas lumping all the biota into one diagonal element would result in a low resolution of the IM and multiple interactions within the diagonal element 'biota'. Instead, biota can be divided into a small number of groups based on e.g. feeding preferences or habitats. Depending on the scale of interest in an assessment, each biosphere component can be further divided into separate IMs introducing a more detailed level of description, but such an extension of the concept is not presented in this report.

3.3 Process interactions

The dynamics of a system can be described in terms of processes acting between the major components (diagonal elements in the matrix). Processes are displayed as off-diagonal elements in the matrix, and represent direct interactions between two biosphere components. To specify all processes in an ecosystem model is not doable and from the perspective of a safety assessment also unnecessary. As an example from the biosphere IM, the process 'reactions' includes chemical reactions in water, regolith, atmosphere and within biota (metabolism), which means that this one process includes hundreds (or even thousands) of possible sub-processes if all separate reactions were treated individually. Instead, processes similar to each other and/or with a similar mechanism or result are grouped into broader processes.

Due to the complexity of ecosystems, different authors sometimes subdivide the biosphere processes differently than done here. The definitions in this report should therefore be regarded as those of SKB and may differ somewhat from other definitions in the literature. A list of process names commonly used in literature and used in previous assessments at SKB is given in Appendix D of this report and the processes are described thoroughly in Chapter 6.

There are processes that are not included in the list of processes in this report, although they are the cause of other processes that are described. One example is gravitation, which causes deposition (which is described). Gravitation is explained by the general theory of relativity, but this level of detail is not considered to be relevant in describing radionuclide behaviour in a safety assessment. Instead, only processes that directly affect radionuclide transport or accumulation are considered. Similarly, process interactions are only considered to be important to consider in a safety assessment if they have an effect on the transfer and accumulation of radionuclides in the biosphere components, i.e. although a process may lead to an alteration in the species present this is not important for accumulation and transport of radionuclides as long as the ecosystem function remains substantially unchanged and this process interaction does not need to be considered in the safety assessment.

3.4 Features

When the IM for the biosphere was updated from previous versions, only physical components were placed on the lead diagonal and properties were not permitted to be defined as elements of the lead diagonal. However, the properties of the physical components may have a large effect on the system and affect the rates or directions of processes. Therefore, features (variables) were added as characteristics of the lead diagonal elements of the biosphere IM. Thus, a large difference from previous SKB IM is that the previous diagonal elements temperature, water composition and radionuclide inventory are treated as features in this IM. In addition, geometry, material composition and stage of succession were added to make the list of features more complete. In this way only physical components are now shown on the lead diagonal and transport and accumulation is more clearly visualised. A drawback of this approach is that the processes acting between the features within the physical component are not as clearly shown. Instead the effects of the features on the processes are described more in detail in Chapter 7 and in Appendix C.

4 Biosphere components

The biosphere components identified are physical component of the biosphere. In total 10 components were identified and these represent different environmental media (regolith, water in regolith, surface water, and atmosphere) and organism groups (primary producers, decomposers, filter feeders, herbivores, carnivores, and humans). In addition two boundary components (geosphere and external conditions) are included in the IM. In the text below, references to literature are made where appropriate. The description of components in the following text is general and applicable to all kinds of ecosystems, although filter feeders are absent in terrestrial ecosystems.

4.1 Regolith

The regolith covers almost the Earth's entire surface. Regolith is composed of weathered rock debris covering the rock beneath it, as well as glacial and postglacial deposits, newly formed soils and sediments including dead organic material (Jones et al. 1992). In addition, the surface of rock outcrops is included in the SKB definition. Topography, i.e. the relief and form of the land is included as the geometric extent, i.e. position (x,y,z) of the base and the surface of the regolith. Moreover, all kinds of man-made constructions are included, e.g. roads, houses, etc. The geometry, structure and porosity of the regolith are included in the diagonal element. This diagonal element was called Quaternary deposits (QD) in SKB's initial biosphere IM, but this term is replaced since the category is wider than Quaternary deposits and also covers deposits laid down in the far future.

4.2 Water in regolith

Water in regolith is the water in the saturated zone of the regolith and the pore water in the unsaturated zone. Frost and ice are also included. Wells are included in this diagonal element, but deeply drilled wells into the geosphere are included in the diagonal element geosphere. This diagonal element includes both quantity and composition (as the feature water composition) in regolith. Water in regolith does not include the water in the bedrock, as this is handled in the geosphere matrix. This diagonal element should not be confused with the classical definition of groundwater, which excludes pore water in the unsaturated zone and includes deep groundwater in the geosphere (Freeze and Cherry 1979).

4.3 Surface Waters

Surface water is here defined as water on the Earth's surfaces, collecting on the ground, or in streams, rivers, wetlands, lakes, open water, and oceans, as opposed to water in rock, regolith or atmosphere (Heath 1987). Rainwater on rock surfaces, snow and ice on land and on water, as well as droplets on e.g. vegetation are included in surface water. This diagonal element includes both the quantity and chemical composition of surface water, including both dissolved elements and particulate matter. Particulate matter is not treated as a separate compartment as is done with regolith and water in regolith, since the particulate matter is a small fraction in water and follows the water fluxes. Similarly, water and particles in the atmosphere are not treated as a separate compartment. This contributes to keep the number of diagonal elements to a manageable number, but leads to some processes (e.g. sorption) occurring within the diagonal element. All physical states of water are considered, i.e. this diagonal element includes also frost and ice. Atmospheric water belongs to the component gas and local atmosphere, in contrast to the classification made by some other authors, e.g. Watson and Burnett (1993) who includes rain, fog and snow in surface water.

4.4 Gas and local atmosphere

Gas and local atmosphere includes the local atmosphere and gas in regolith and in water in regolith as well as gas bubbles in surface water. Gas flow and gas composition are included in this element which, therefore, includes wind and the content of particulates in the local atmosphere, i.e. water droplets, pollen, etc. Gas bubbles in water are included in this diagonal element, whereas dissolved gases in surface waters are included in the diagonal element 'surface waters'. The local atmosphere is defined as the layer of the atmosphere above the studied area that participates in gas exchange with the studied area. It is surrounded by the atmosphere, which is a boundary to the biosphere system and is included in the diagonal element external conditions.

4.5 Primary producers

Primary producers are autotrophic organisms able to use sunlight or the oxidation of inorganic compounds as an energy source to synthesise organic compounds from inorganic carbon sources. The organic compounds are used as fuel for cellular respiration and growth. Primary producers include green plants, algae and autotrophic bacteria (e.g. Campbell 1993, Maier et al. 2009). Characteristics of primary producers include species, quantity (i.e. biomass) and geometry. Examples of functional groups that are included are grasses, herbs, bushes, trees, phytoplankton, microphytobenthos, and aquatic macrophytes and macroalgae.

4.6 Decomposers

Decomposers are organisms (bacteria, fungi or animals) that feed on dead plant and animal matter and break down complex organic compounds into carbon dioxide, water and inorganic compounds (e.g. Begon et al. 1996, Porteous 2000). In a sense, most carnivores live on dead material as they most often kill their prey, and plant matter is dead before its digestion in herbivores begins. However, decomposers do not actively affect the rate at which their food resource becomes available, but are instead dependent on other factors such as senescence, illness, fighting or shredding of leaves, whereas herbivores, filter feeders and carnivores directly affect the rate at which their resources become available (Begon et al. 1996). Characteristics of decomposers include species, quantity (i.e. biomass) and geometry. Examples of functional groups that are decomposers are bacteria, soil fauna (e.g. earthworms), and some species of aquatic benthic fauna.

4.7 Filter feeders

Filter feeders are aquatic organisms that feed on particulate organic matter and small organisms (phytoplankton and zooplankton) filtered out by circulating the water through the animal's system. Filter feeders include a wide range of animals such as bivalves (e.g. mussels), sponges, crustaceans (e.g. shrimps) and even whales. Filter feeders are an important group of organisms in aquatic ecosystems, as they can greatly affect the amount of particulate matter and nutrients in the water, and transport particulate matter from the water column into biota (e.g. Holland 1993, Soto and Mena 1999, Wilkinson et al. 2008). Hence they are treated as a separate diagonal element, althoughconceptually they are a mix of decomposers, herbivores, and carnivores. The characteristics of filter feeders include species, quantity (i.e. biomass) and geometry.

4.8 Herbivores

Herbivores are animals that feed on primary producers, i.e. plants, algae and autotrophic bacteria. Omnivores are functionally a mix of herbivores and carnivores and are included both here and in carnivores (see below). Characteristics include species and quantity (i.e. biomass) of herbivores. Examples of herbivores include some species of insects, rodents, fish and larger mammals.

4.9 Carnivores

Carnivores are animals that feed on other animals. Omnivores are functionally a mix of herbivores and carnivores and are included both here and in herbivores (see above). Characteristics include species and quantity (i.e. biomass) of carnivores. Examples of carnivores include some species of insects, birds, fish and mammals.

4.10 Humans

Humans are defined as all human beings living in the area affected by potential releases of radionuclides from the repository under consideration in the safety assessment. This diagonal element includes, characteristics, the number of persons but also their activities, e.g. fishing. Water pumping and anthropogenic releases (of e.g. water, chemical substances or heat) are included (aquatic) as well as agriculture, irrigation and construction (terrestrial).

4.11 Boundary components

4.11.1 Geosphere

Geosphere is the bedrock surrounding the repository. It also includes deep groundwater and gases present in the saturated zone in the bedrock. Thus, deeply drilled wells are also included in this diagonal element since, although the utilisation is at the surface, the water is extracted from the geosphere. The geosphere is a boundary to the biosphere, and the interface is defined as the top surface of the weathered rock at the interface with the regolith, i.e. the geosphere is the solid rock below sediments (aquatic systems) and soils (terrestrial ecosystems). In the SKB definition rock outcrops are part of the regolith. However, it is only the top surface of the rock outcrops that are considered part of the regolith, just below the surface the rock outcrops become parts of the geosphere In the literature, the geosphere is often defined as the densest part of the Earth, consisting mostly of rock and regolith (Skinner and Porter 2000) thus deviating from the SKB definition by also including regolith. In SKB's IM, regolith is treated as a separate diagonal element (see below). The components of the geosphere are further described in (SKB 2001, 2010b).

4.11.2 External conditions

External conditions are all external factors that affect the local conditions considered within the biosphere IM or that are affected by the biosphere identified in the matrix. External conditions include surrounding ecosystems and the atmosphere above and beyond the lateral boundaries of the local atmosphere. They also include global conditions such as global climate and solar insolation.

5 Features

A feature is here a property, a function, a condition or an attribute affecting a biosphere component or affecting the *rate or direction* of a process interaction between two components. A number of features affect each physical component and the process interactions between physical components. Six important features were identified for the biosphere components and processes: geometry, material composition, radionuclide inventory, stage of succession, temperature and water composition.

The features included in the biosphere IM represent the internal characteristics of the components and the effects of the features within the system and external forcing factors are not included. For example, the feature temperature refers to the internal temperature of the biosphere components and not to large-scale climate factors. The effects of large-scale climate changes are instead covered by processes acting from the boundary condition 'external conditions' on the different biosphere components, i.e. solar radiation affects the temperature of the biosphere components by light-related processes.

A systematic description of how the features affect processes and vice versa is given in Appendix C. Features are also included in the description of the process interactions between different biosphere components in Chapter 7. Below are given brief definitions of the different features included in the biosphere IM.

5.1 Geometry

Geometry includes geometric descriptions of the landscape such as topography and bathymetry, depth and volume of regolith, peat, water etc. This feature also includes the geometry of organisms, i.e. their shape, surface area and volume.

5.2 Material composition

Material composition includes chemical composition (e.g. concentration of minerals and nutrients) as well as physical features such as grain size and porosity.

5.3 Radionuclide inventory

Radionuclide inventory include radionuclides and their activities in all physical and biological components of the biosphere system in question (i.e. in all physical diagonal elements such as regolith, surface waters, and biota).

5.4 Stage of succession

Stage of succession is a feature used in the biosphere IM to determine differences between ecosystems. The landscape in Forsmark continuously evolves due to ongoing shore line displacement and associated succession of the ecosystems. Thus, marine ecosystems are typically gradually transformed into lakes which by succession turn into wetland and forests. In addition, wetlands can be drained by humans and used for agriculture. Different process interactions are important for different stages of this ecosystem succession. The biosphere IM is generally applicable to all kinds of ecosystem and the feature 'stage of succession' can be used to evaluate for which ecosystems specific processes may be sufficiently important for them to be taken into account in a safety assessment, i.e. the stage of succession defines whether the ecosystem is a marine basin, lake, stream, forest, wetland, or agricultural land.

5.5 Temperature

Temperature is the unique physical property that determines the direction of heat flow between two objects placed in thermal contact In SKB's IM, temperature is restricted to the temperature in the physical component of the system of interest (i.e. all physical diagonal elements such as geosphere, regolith, biota, and water). Temperature is dependent on climate, and local effects on climate are associated with this feature, whereas large-scale climate systems and their impacts belong to the diagonal element 'external conditions'.

5.6 Water composition

Water composition comprises dissolved elements and compounds, colloids and suspended particles (including dead organic matter) in the biosphere components. The content of ions and elements determines e.g. pH-values, salinity, and nutrient concentrations. Thus, water composition is important to the presence and viability of biotic components and process rates. Various transport, chemical and biological processes affect water composition.

6 Biosphere processes

In total, 50 processes were identified as potentially important for ecosystem functioning, landscape development, and for transport and accumulation of elements and radionuclides in the biosphere. To more easily illustrate the different kinds of processes acting in the biosphere they are grouped into the following categories 1) Biological processes, 2) Processes related to human behaviour, 3) Chemical, mechanical and physical processes, 4) Transport processes, 5) Thermal and radiological processes, and 6) Landscape development processes. Synonyms and sub-processes (some processes are composed of several sub-processes) are listed in Appendix D. A brief description of the processes is given below whereas a more detailed description of where and how they act within the biosphere is given in Chapter 7.

NEA (2000) has produced a database of features, events and processes (FEPs) used for safety assessments of repositories for radioactive waste by several countries. Definitions of NEA FEPs and how these correlate to the processes used by SKB can be found in SKB's FEP database. In addition, in SKB's FEP database the influences of features (variables) on the processes (and vice versa) are also described.

6.1 Biological processes

Biological processes are processes that are dependent on organisms. One way of exposure to radionuclides is via intake of water and food and thus the distribution of biota and food-web interactions are important to consider. In addition, biota may influence the distribution of radionuclides in abiotic pools by e.g. disturbing sediment or affecting water composition. The biotic processes may involve both humans and other organisms. Processes that are strictly related to humans are addressed in Section 6.2.

6.1.1 Bioturbation

Bioturbation is the mixing of particles in both aquatic and terrestrial regolith by plants, animals, bacteria and fungi (e.g. Grayham 2005). This soil or sediment turnover leads to a redistribution of contaminants such as radionuclides (e.g. Krantzberg 1985, Thorsson et al. 2008). The process also adds oxygen to the soil and sediment. Examples of bioturbation are earthworms exploiting the soil for food, clams seeking shelter in the sediment and humans ploughing fields. Bioturbation affects regolith chemistry and the quantity of air and water in the regolith.

6.1.2 Consumption

Consumption is the ingestion of matter by organisms (particulate matter and other organisms). Besides the active ingestion of food, particles (e.g. regolith) may also be unintentionally consumed. The intake of water, dissolved elements and gases is not included in consumption, but is treated as 'uptake' (see the process below). Consumption by organisms is an important pathway for the transport of radionuclides from the base of the food web to top predators and to man.

6.1.3 Death

Death is the production of dead organic matter generated by organisms. The dead organic matter may originate from the death of organisms, but may also be generated by scattering (e.g. leaves and branches falling from trees). Both the generation and consumption of dead organic matter may redistribute elements among organisms, and also between biota and water, soils and sediments.

6.1.4 Decomposition

Decomposition is the disintegration of dead organic matter by decomposers (Begon et al. 1996). By means of decomposition, energy-rich organic molecules are broken down to carbon dioxide, water and inorganic nutrients and/or less complex organic molecules. Uptake and excretion by decomposers are, as with all other biota, treated as the processes 'Uptake' and 'Excretion'. However, in addition to uptake and excretion, decomposition affects the available quantities of non-degradable matter and releases water from organic matter, which may influence water quantities in regolith water and water composition. Moreover, decomposition may release radionuclides accumulated in dead organic matter. The rate of decomposition is dependent on the chemical character of the dead organic material and environmental conditions such as climate and soil type (e.g. Meentemeyer 1978, Enríquez et al. 1993, Bellamy et al. 2005). It should be noted that the rate of decomposition may be important, and that a reduced decomposition rate results in the generation and expansion of carbon reservoirs and associated elemental accumulation in the regolith, e.g. peat and sediments.

6.1.5 Excretion

Excretion is the release of elements and compounds from organisms to the surrounding media. Excretion can occur through special parts or organs such as stomata in plants, excretory organs in animals or directly through cell membranes (e.g. sweat) (Raven et al. 1992, Cavendish 2010). Faeces are included in excretion. Release of CO_2 by respiration is also an example of excretion. Excretion influences the composition of water, gas, regolith and biota. Consequently, excretion of radionuclides by biota can be important for their transport and accumulation in the biosphere.

6.1.6 Food supply

Food supply is the production of food and the process by which it is made available to consumers (Jones et al. 1992). Primary producers, animals and dead organic matter may be utilised as food sources by other organisms and thereby comprise a supply of food to consumers. Thus, food supply is a counterpart to consumption, which is the demand for food, while food supply is the delivery of food. Dissolved elements that are consumed by microorganisms are treated in the process 'element supply'. Besides supplying food, materials and organisms may be utilised by humans for other purposes, but this is treated separately in the process 'material supply'.

6.1.7 Growth

Growth is the generation of biomass by organisms. Growth is dependent on primary production and consumption. However, not all chemical energy fixed by photosynthesis (gross primary production) is converted to new biomass; a large part is also lost due to cellular respiration (e.g. Thornly 1970, Amthor 2000) and exudates (e.g. Goto et al. 1999, Sorrell et al. 2001, Descy et al. 2002). Thus, for primary producers, growth equals gross primary production minus respiration (i.e. net primary production) minus excretion. Similarly, not all material consumed by consumers is converted to new biomass; some is lost due to excretion (e.g. respiration and faeces). Growth may be important in the radionuclide assessment, as an increased biomass may dilute radionuclides in organisms (IAEA 1996).

6.1.8 Habitat supply

Habitat supply is when organisms or abiotic components of the environment provide a substrate or shelter for other organisms. Examples of habitats are: a piece of land that can be cultivated, rock substrate for barnacles or bladder wrack, and a tree trunk for insects. Surface water can also supply a habitat for organisms, provided the water composition is suitable.

6.1.9 Intrusion

Intrusion is defined here as the process whereby organisms (including humans) enter the repository. Organisms can cause intrusion by e.g. drilling, locomotion, or growth. Intrusion may affect rock structures, hydraulic conductivity, the potential for erosion, the physical and mechanical properties of the repository, oxygen conditions and the quantities of biological material near the repository (SKB 2001). This is one of the processes whereby the biosphere affects the geosphere and is further treated in the geosphere IM (SKB 2001).

6.1.10 Material supply

Material supply is the amount of material that is available for human utilisation for purposes other than feeding. Primary producers are commonly utilised for other purposes than food, e.g. as paper, building material, cooking fires, clothing (e.g. cotton). The geosphere supplies minerals and fossil fuels. Other examples of material supply are when humans utilise shells, skin, fur and ivory from animals in handicrafts and for clothing (Raven et al. 1992, Rahme and Hartman 2006).

6.1.11 Movement

Movement is the locomotion of organisms in surface waters. The presence and movement of organisms in surface waters may have an influence on surface water movement. Filter feeders can have an effect on surface water movement by creating water flow with their filtering organs, and in some areas of the world the movements of large herbivores, such as hippopotamus, may create surface water movements. There are large herbivores and carnivores in Sweden – for example elk (moose), bear and seals – but they do not affect surface water movement to any appreciable extent.

6.1.12 Particle release/trapping

Particle release/trapping is the release of particles from organisms to the environment, or the trapping of particles in the environment by organisms. Release of particles occurs via e.g. fragmentation, spawning, pollen and seed release. In terrestrial areas, particle release often occurs seasonally, with large releases of e.g. pine pollen in the spring, which can reach large areas (e.g. Di-Giovanni et al. 1996). Similarly, in aquatic areas, large quantities of particles may be released in a short period of time by spawning animals (e.g. Cuzin-Roudy 2000). Organisms trap particles on e.g. fur, gills and slime. In aquatic ecosystems, filter feeders are responsible for most particle trapping and can greatly affect the clarity and nutrient concentrations of the water, as well as transport of particulate matter from the water column into biota (e.g. Holland 1993, Soto and Mena 1999, Wilkinson et al. 2008). In terrestrial areas, particles may also be trapped on animals, but then the trapping is more unintentional. The presence of particles affects the composition of water and air. This process may be important for the transport of radionuclides attached to particle surfaces.

6.1.13 Primary production

Primary production is the fixation of inorganic carbon by primary producers (e.g. Campbell 1993, Moran 2006). Green plants, algae and some bacteria produce organic compounds from inorganic substances through photosynthesis (using sunlight as an energy source) and chemosynthesis (using chemical compounds as energy source) (e.g. Raven et al. 1992, Maier et al. 2009). Primary production here refers to gross primary production, i.e. the total fixation of inorganic carbon by primary producers. Net primary production is the quantity (carbon) produced and is the net effect when respiration is subtracted from gross primary production. Net primary production may be used as food for herbivores, which is treated in the process 'Food supply' (see above). The rate of primary production is dependent on many factors, of which some important ones are: solar insolation, climate, substrate, and area of leaves and other green parts of the plants (e.g. Campbell 1993, Galston et al. 1980, Kuckuck et al. 1991). The uptake of a number of radionuclides by biota is directly dependent on primary production, making this process a transport pathway for radionuclides from abiotic to biotic components.

6.1.14 Stimulation/inhibition

Stimulation/inhibition occurs when a component influences another component positively or negatively. Abiotic components may stimulate biotic components by providing favourable chemical conditions (e.g. pH and salinity), a favourable temperature, wind shelter etc. Similarly, abiotic components may inhibit biota by providing unsuitable living conditions. Biotic components may also stimulate or inhibit each other. One example of stimulation is grazing, which stimulates grazing-resistant species of primary producers and may even increase the biomass and primary production of the plant communities (e.g. McNaughton 1985, Steinman 1996). Organisms may inhibit each other by e.g. toxin production, parasitism, and competition for space and resources (e.g. Berger and Schagerl 2003, Legrand et al. 2003, Stiling 1996). Humans can potentially have a great impact on ecosystems by stimulation and inhibition of biota in connection with their utilisation of land for food and material production, and there are global examples of large human impacts on land use in natural ecosystems (e.g. Foley et al. 2005).

6.1.15 Uptake

Uptake is the incorporation of elements or water from the surrounding media by organisms (including humans). Organisms may take up water and substances by drinking, inhalation, root uptake, or directly through cell membranes. Uptake and excretion of radionuclides by organisms affects the concentrations of radionuclides in the organisms as well as in other components of the biosphere system.

6.2 Processes related to human behaviour

Human behaviour may have large effect on the biosphere, e.g. by introducing species of biota or chemical elements or by disturbing or removing material in large quantities. Water use, material use, anthropogenic release, and species introduction/extermination are processes related to human behaviour.

6.2.1 Anthropogenic release

Anthropogenic release is the emission of a substance into the air or water, or the deposition of a substance on land (cf. Porteous 2000). It also includes release of water and energy (heat) mediated by humans. Anthropogenic release may affect the chemical composition and temperature of the environment, which in turn may be important for biotic components and biotic processes.

6.2.2 Material use

Material use is human utilisation of the environment for purposes other than feeding (see 'Consumption'), drinking (see 'Uptake') and water use (see below). Minerals and fossil fuels in the geosphere, wind (local atmosphere) and biota may be used for energy production, clothing (e.g. fur and cotton), paper production, colouring, and building material (wood, reed, leaves). All these activities can affect the accumulation and transport of radionuclides in the biosphere system as well as the doses to humans. Human material use can also affect species distribution, biomass and production.

6.2.3 Species introduction/extermination

Species introduction/extermination is the introduction or extermination of species to/from the modelled area by human activities. Different pathways for introducing species are e.g. agriculture, aquaculture, pest control and unintentionally by import of other items. There are several examples of introduction of alien species in the recent past where the introduced species have acclimatised to the new environment in Sweden. Some of the best known are the introduction of mink (*Mustela vison*), zebra mussel (*Dreissena polymorpha)* and the crayfish species *Pasifastacus leniusculus* (e.g. Gerell 1969, Söderbäck 1995, Brunberg and Blomqvist 2001, Josefsson and Andersson 2001, Westman 2002, Minchin et al. 2002). Although the examples mentioned above have had rather negative implications for the ecosystems where they have been introduced, introduction of species may also have positive effects for humans and, in a longer time perspective, the majority of crop species used in Sweden have been introduced. In addition to introducing alien species, humans may eliminate species from an area by hunting, collecting or disturbing living habitats, and a number of populations and species in Sweden and worldwide are currently threatened with extinction (Ehrlich and Daily 1993, IUCN 2010). Examples of species already exterminated in Sweden are the middle spotted woodpecker *(Dendrocopos medius)* and the European bison (*Bison bonasus bonasus)* (Benecke 2005, http://www.slu.se/artdatabanken/).

6.2.4 Water use

Water use is the amount of water used by humans for purposes other than drinking. Examples of water use are energy production, irrigation, sewage flushing, washing clothes, showering, and losses in the supply chain (e.g. leakage from pipes) (Twort et al. 2000). Irrigation may increase radionuclide concentrations in food.

6.3 Chemical, mechanical and physical processes

Chemical, mechanical, and physical processes are processes that occur due to mechanical forces or physical and chemical laws. Chemical, mechanical and physical processes can influence the state of elements and compounds, which can be important for the transport of radionuclides. For example, in some physico-chemical states elements are tightly bound to particles and in other states they may be easily dissolved and transported by water. Moreover, these processes can affect the bioavailability of radionuclides, depending on whether the radionuclides are present in physico-chemical forms that are readily taken up by organisms.

6.3.1 Change of pressure

Pressure is the amount of force acting on a unit area (Daintith 1985). Here, pressure refers to the pressure of the air and water, and change of pressure refers to the change in this pressure. The process also includes adiabatic temperature change, i.e. heating or cooling as a result of pressure change. The pressure exerted by the air (atmospheric pressure) varies widely on the Earth and affects climate, weather, sea level, water transport etc (e.g. Lehmann et al. 2002 and references therein). The pressure exerted by water on the sea floor is dependent on the sea level, which may change due to eustasy and isostasy (see the processes 'Sea level change' and 'Change in rock surface location').

6.3.2 Consolidation

Consolidation is any process whereby loosely aggregated, soft, or liquid soil materials become firm and coherent rock. The load expels pore water and pore air and decreases the regolith volume (Terzaghi 1943). The transformation of regolith to solid rock is a slow process that entails a gradual reduction in volume and increase in density in response to an increased load or compressive stress. This process is affected by the weight of regolith (thickness and density). As a consequence of consolidation, radionuclide-contaminated air or water may be transported out of the regolith layer together with the water (Butalia 2005). This is one of the processes whereby the biosphere affects the geosphere and is further treated in the geosphere IM (SKB 2001). Consolidation is also used by SKB to describe the compactation of regolith, e.g. during draining of wetlands.

6.3.3 Element supply

This is the amounts of elements and other substances from a reservoir that are available for use by humans and other organisms. An element is commonly defined as a substance that cannot be broken down into simpler substances by chemical methods (Daintith 1985, Porteous 2000). Here the definition is somewhat broader and includes, in addition to elements, dissolved or gaseous compounds that are available for uptake by organisms. Examples of element supply are the reservoirs of CO_2 and nutrients dissolved in water that are available for aquatic primary producers to utilise in primary production, or the amount of oxygen available for respiration by consumers. The demand for nutrients for primary production is often greater than the supply, in which case element supply will limit primary production (e.g. Vollenweider 1976, Evans and Prepas 1997, Hyenstrand et al. 2001).

6.3.4 Loading

Loading is the exertion of force caused by the weight of material (regolith or ice) on the underlying rock. The weight of regolith (thickness and density) affects the mechanical stress in the geosphere and thereby the occurrence of fractures through which groundwater can reach the surface (e.g. Owen et al. 2007 and references therein). Similarly, changes in the thickness of an ice sheet during a glaciation will affect the mechanical stress in the rock. This is one of the processes whereby the biosphere affects the geosphere and is further treated in the geosphere IM (SKB 2001).

6.3.5 Phase transitions

Phase transitions are changes between different states of matter: solid, liquid and gas (e.g. Masterton and Hurley 2008). Phase transitions occur as a result of changes in temperature and/or pressure and sometimes in connection with reactions. Phase transitions comprise a number of sub-processes which may be important for the transport of radionuclides in the biosphere. Examples of sub-processes are evaporation and condensation (i.e. transformation of water from liquid phase to gaseous phase and vice versa), dissolution and degassing (flux of gas across the water/atmosphere and soil/atmosphere interfaces), and freezing of water. Phase transitions affect humidity and the chemical composition of water, atmosphere and regolith (Guzzi et al. 1990, Horne and Goldman 1994).

6.3.6 Physical properties change

In the biosphere IM, physical properties change is limited to changes in volume, density and/or viscosity of water. Other physical properties e.g. colour, density, electric charge, length, pressure, are not included. Temperature has a strong effect on the density of water. Freshwater reaches its maximum density at approximately 4°C. Water volume is dependent on density, which is one of the reasons for sea-level rise due to global warming (e.g. Whitehouse 2009, Brydsten et al. 2009). In addition to temperature, volume and density are also affected by pressure and salinity, where high pressure and high concentration of dissolved salts lead to increased density and decreased volume. Fluid viscosity, which is a measure of the resistance of the fluid to shear forces, is also affected by temperature and decreases with temperature (Wetzel 2001, Seeton 2006).

6.3.7 Reactions

A chemical reaction is a change in which one or more chemical elements or compounds form new compounds (Daintith 1985). The term ‘reaction’ is limited here to chemical reactions, excluding weathering, decomposition and photosynthesis (treated as separate processes). Reactions can release or consume heat. They affect colour and density and can induce phase transitions. Reaction includes reaction rate, which is affected by the temperature. Although many reactions will have a limited direct effect on transport and accumulation of radionuclides, they may be important for ecosystem function and are thereby an indirect effect on transport and accumulation of radionuclides.

6.3.8 Sorption/desorption

Sorption is the process whereby dissolved substances adhere to surfaces or are absorbed by particles (e.g. soil or sediment particles), whereas desorption is the reverse process, whereby substances are released (Dunnivant and Anders 2006, Porteous 2000). Sorption includes adsorption (association usually due to ion exchange at the surface of a particle), partitioning (hydrophobic substances associate with the surface of a particle) and absorption (sorption into the interior of a particle), as the end result of all these sub-processes is association of substances to particles. Moreover, the sub-processes are hard to distinguish from each other in practice (Schnoor 1996, Dunnivant and Anders 2006). Sorption/desorption is affected by the chemical composition, charge and surface area of the solid matter, as well as the sorption properties of the dissolved substances. Water composition and the quantity of particles in the water in the different parts of the biosphere system affect sorption/desorption and, therefore, the concentrations of radionuclides and other elements in water and on solid phases in the different parts of the biosphere system. The distribution coefficient Kd is normally used as a measure of this complex interaction.

6.3.9 Water supply

Water supply is the flux of water that can be utilised by organisms in the ecosystem (including humans). This definition is somewhat broader than the one commonly used in the literature, where water supply is often restricted to the supply of water to humans (Twort et al. 2000). The supply of water to organisms may be utilised for drinking (see ‘Uptake’), and humans may also use the water for other purposes such as irrigation, washing, or industrial use (see ‘Water use’).

6.3.10 Weathering

Weathering is the disintegration and decomposition of rock and regolith into smaller pieces (Jones et al. 1992, Skinner and Porter 2000). This process does not include erosion, i.e. transport of matter from the source, which is treated under 'Relocation'. Weathering can be chemical, mechanical and/or biological. Chemical weathering dissolves and disintegrates solid matter due to the chemical action of water, oxygen, carbon dioxide and organic acids. Mechanical weathering is caused by the physical action of frost, temperature change, wind and salt crystallisation, whereas biological weathering is the breakdown of rocks and stones and their constituent minerals by the actions of plants and animals.

6.3.11 Wind stress

Wind stress is a mechanical force generated by wind affecting surfaces in the biosphere. When the wind speed is high the pressure acting on the biosphere is high. Wind stress affects surface water by influencing e.g. wave formation (see 'Convection'), and the quantity of water contained in sea spray (see 'Resuspension').

6.4 Transport processes

Transport processes are processes whereby elements and substances are transported from one point to another in a system. Transport processes can have a large effect on where in the system radionuclides end up or if they are transported out of the system in question.

6.4.1 Acceleration

Acceleration is the change in velocity of a gas, liquid or body over time and/or the rate and direction of velocity change. Acceleration may be either positive or negative, i.e. either an increase or a decrease in speed. Acceleration is influenced by both biotic and abiotic components in the biosphere, such as topography, type and location of primary producers, man-made buildings etc (e.g. Givoni 1998, Gerhard and Kramer 2003, Rueda at al. 2005, Koletsis et al. 2009). The velocity of wind and water in turn influences the mixing of the water column and residence time (convection), as well as living conditions for humans and other organisms (see stimulation/inhibition)

6.4.2 Convection

Convection is defined here as the transport of a substance (e.g. water) or a conserved property (e.g. temperature) in a liquid or gas. The definition includes convective and advective transport as well as diffusive transport. In hydrology, oceanography, meteorology and other large-scale environmental sciences, the processes of diffusion and advection are often distinguished (e.g. Richards and Bouazza 2001). Molecular diffusive transport (or mixing) is caused by random movement of molecules within the fluid/gas, whereas advective (and convective) transport refers to transport of heat or mass by bulk movement of surrounding media (e.g. Schnoor 1996, Incropera and DeWitt 1990). Convection is defined in certain disciplines as a special case of advection, where the bulk movement is initiated by a density gradient (e.g. heat or salinity) in the surrounding media, causing a vertical flow (Skinner and Porter 2000, Manahan 2004). In this report, all advective, convective and diffusive transport is treated together in order to keep the number of processes manageable, and the process is called convection. Examples of convection in ecosystems are river flow, groundwater discharge/recharge, and mixing in lakes (spring and autumn turnover).

6.4.3 Covering

Covering is the process whereby something, such as ice or vegetation, covers a surface and thereby reduces the incoming light, as well as reducing the exchange of gases and particles between the surface water and the atmosphere (Loose et al. 2009). Ice cover on a lake influences the quantity of water that can evaporate, the exchange of oxygen and carbon dioxide between the atmosphere and the surface water, and surface water movements. Dense coverage by primary producers has a similar impact.

6.4.4 Deposition

Deposition is the transfer of a material or an element due to gravitation to a surface of any kind. The process thereby includes both sedimentation and atmospheric precipitation. Atmospheric precipitation occurs as dry deposition or wet deposition (rain, snow and hail) (Altwicker et al. 1997). Deposition is affected by the density and volume of the particles and the density of the media they are sinking through (air, water). In addition, advection and turbulence, such as wind velocities and currents, affect deposition. Deposition changes the composition, geometry and porosity of the regolith, amounts of surface water flow, and deposition of radionuclides and other toxicants on the surface regolith may alter the physical and chemical properties (mineralogy) of the surfaces.

6.4.5 Export

Export is defined here as the process whereby something is transported out of the model domain. Anything can be exported, e.g. organisms, water, gas, elements, compounds, and heat. Humans moving from the site (emigration) are also included in this process. Export may be active (intentional migration by organisms) or passive (caused by wind, currents, downstream water discharge, etc). Export of abiotic components affects the temperature and the quantities of elements and other substances at the site. Export of organisms affects the number of inhabitants at the site and related processes such as consumption and production.

6.4.6 Import

Import is defined here as the process whereby something is transported into the model domain. Anything can be imported, e.g. organisms, water, gas, elements, compounds, and heat. Humans moving into the site (immigration) are also included in this process. Import may be active (intentional migration by organisms) or passive (caused by wind, currents, water discharge, etc). Import of abiotic components affects the temperature and the quantities of elements and other substances at the site. Import of organisms affects the number of inhabitants at the site and related processes such as consumption and production.

6.4.7 Interception

Interception is here used to cover all wet and dry deposition of elements that are intercepted /retained on vegetation and do not immediately infiltrate into the ground or take part in subsurface transport or runoff processes (e.g. IAEA 1996). It is thus not restricted (as in some studies) to the water in precipitation that is retained on vegetation (e.g. Larcher 1995, Chapin et al. 2002). The amounts of water and elements that are intercepted are influenced by the above-ground biomass, vegetation type, available leaf surface area, deposition quantity, deposition type (dry or wet) and absorption by primary producers (Larcher 1995, IAEA 1996, Breshears et al. 2008 and references therein). Interception may be important from a radiological point of view if radionuclides are present in the atmosphere and thereby fall out by deposition or if radionuclides are present in water that is used for irrigation. The fraction of deposition that is intercepted influences the quantities of radionuclides in the vegetation, and, if that vegetation is consumed, the doses to animals and humans as well.

6.4.8 Relocation

Relocation is the transfer of solid matter and sessile organisms from one point to another. Relocation can be mediated by erosion by water or wind, ice erosion, landslides, or human activities such as digging, soil transport and industrial mining. Relocation may release contaminants and radionuclides to water and air (e.g. Whicker et al. 2006, Cornelissen et al. 2008). Finer particles are resuspended by wind and water, which is treated as a separate process, see resuspension.

6.4.9 Resuspension

Resuspension is the process by which material that has been deposited on a surface is reconveyed into the overlying media (e.g. Weyhenmeyer 1998, Ziskind et al. 1995). In the biosphere, this process can be important at the interface between sediment and the water column, as well as between topsoil and air. Resuspension in aquatic environments increases the surface interaction between particles and the water column, thus affecting sorption/desorption processes. Large quantities of deposited material may be subjected to resuspension in both marine and limnic ecosystems (Weyhenmeyer 1998, Brydsten 2009). The size distribution of the particles in the regolith influences the amount of material resuspended in the water or air and thereby the particulate content in the water or air. Larger particles are treated under relocation.

6.4.10 Saturation

Saturation is defined here as the change in the water content of the regolith. When all pores in the regolith are filled with water, the regolith is said to be saturated (Knapp 1979, Skinner and Porter 2000). The magnitude and direction of water flow in the regolith (convection) influence saturation. The water flow in the regolith depends on precipitation, evapotranspiration, the hydraulic properties of the regolith, porosity etc. Saturation is important for terrestrial biota as it determines the living conditions for plants.

6.5 Radiological and thermal processes

Thermal and radiological processes are those processes that concern temperature, solar insolation and radionuclide-specific characteristics.

6.5.1 Radioactive decay

Radioactive decay is a fundamental process that affects all radioactive (unstable) nuclides. The decay leads to a reduction in activity of a nuclide due to radioactive transformation. Radionuclides decay to other radionuclides or stable elements. Decay of a large amount of unstable radionuclides may have an impact on the composition of water, and decaying radionuclides generate (radiogenic) heat that may affect the temperature in the different components of the biosphere system.

6.5.2 Exposure

Exposure is here meant as the process whereby living or dead organisms/matter are exposed to alpha, beta, gamma or neutron radiation. Exposure can either be external exposure from sources outside the body or internal exposure from sources inside the body. Concentration, location and type of radionuclides in all parts of the biosphere system affect external exposure, whereas concentration, location and type of radionuclides inside organisms affect internal exposure. Exposure to a high dose during a short period of time may cause deterministic health effects, ranging from a slight decrease in blood cell count to certain death. Chronic exposure (or prolonged exposure), even at low doses, is considered to increase the probability of stochastic effects, such as cancer and induction of genetic abnormalities in the off-spring of the exposed individual.

6.5.3 Heat storage

Heat storage (heat capacity) is the ability of materials (solids or liquids) to store thermal energy (Incropera and DeWitt 2007). Heat storage affects the temperature in different components of the biosphere, in both terrestrial and aquatic systems. The heat storage capacity of water is very high, exceeded by only a few substances (such as liquid NH_3) and prevents extreme changes in temperature in aquatic ecosystems (Sverdrup et al. 1942, Wetzel 2001). In addition, the specific heat storage of water affects stratification and mixing as well as convection in lakes and oceans (e.g. Horne and Goldman 1994, Wetzel 2001). Although the heat capacity is lower in the regolith than in water, the density and heat properties of the regolith determine the amount of heat that can be stored and thereby also influence the temperature in terrestrial ecosystems.

6.5.4 Irradiation

Irradiation (by ionising radiation) is the process whereby an object is exposed to radiation and absorbs energy (Lamarsh and Baratta 2001). Irradiation by radionuclides in regolith and water in regolith may affect the mineralogical structure of these materials.

6.5.5 Light-related processes

Light-related processes are those that involve light entering the biosphere (insolation) and processes associated with this, i.e. absorption, scattering and reflection. Light-related processes do not include photosynthesis, which is treated as a biological process (primary production). A number of factors (such as water composition, extent and type of vegetation, presence of snow and wave formation) influence the degree of light reflection, scattering and absorption. Light-related processes in turn affect other components of the biosphere. For example, the degree of insolation (and the degree of absorption/scattering/reflection of radiation) affects temperature and photosynthesis (e.g. Guzzi et al. 1990, Horne and Goldman 1994, Wetzel 2001).

6.5.6 Radiolysis

Radiolysis is the disintegration of molecules caused by radiation (SMS TNC 1990). In principle, radiolysis could be disintegration of molecules other than water. In practice, radiolysis of water is of predominant importance. Radiolysis causes radiolytic decomposition of the water and thereby affects the water composition in the different components of the biosphere system. Radiolysis can also locally modify redox conditions and thereby the speciation and solubility of other compounds (Choppin et al. 2002).

6.5.7 Radionuclide release

Radionuclide release is the release of radionuclides from a repository for solid radioactive waste via the geosphere to the biosphere.

6.6 Landscape development processes

The type of ecosystem (marine, limnic or terrestrial) and the geometry of the landscapes influences the transport and accumulation of radionuclides. Therefore, processes affecting landscape development can be important to consider in a safety assessment.

6.6.1 Change in rock-surface location

Change in rock-surface location refers to vertical changes in the rock-surface location due to tectonic, isostatic rebound or repository induced changes. Isostatic rebound is recovery from the load imposed on the land during an ice age, which causes depression of the crust (e.g. Kehew 1988, Fowler 1990). As soon as the pressure starts to decrease due to thinner ice cover, the crust starts to rebound (isostatic rebound). The isostatic rebound leads to shoreline displacement (land-rise), whereby new terrestrial areas and lakes emerge from the sea. Isostatic rebound and sea-level change (see below) are the two factors that determine the location of the shoreline and hence have a significant impact on future ecosystems. However, a change in rock-surface location may also occur without altering the type of ecosystem, i.e. a terrestrial point in the landscape may continue to be terrestrial after a change in rock-surface location. Repository induced changes can be caused by e.g. collapse of caverns resulting in cave-in of surrounding rock or neotectonic movements as earthquakes (Skinner and Porter 2000, Lagerbäck et al. 2005). This affects the stress conditions in the surrounding rock and may affect the height of the regolith.

6.6.2 Sea-level change

Sea-level change is the rise and fall of the sea level. A rise in sea level can occur due to an increase in the height of the ocean surface (for example, due to a change in the geometry of the surface of the Earth, an increase in the volume of water in the oceans, or a decrease in the storage capacity of the oceans) and/or a drop in the height of the land (for example due to ice-sheet loading or tectonic activity, see ´Changes in rock-surface location' above) (Whitehouse 2009). Conversely, a fall in relative sea level can occur due to a fall in the height of the ocean and/or a rise in the height of the land surface brought about by the opposite processes to those described above. At any point in time, the rate of relative sea-level change is governed by a combination of these factors. At present, worldwide sea levels are rising due to expansion of the water volume with increasing temperatures and due to melting of continental ice caused by global warming (e.g. Church and White 2006, IPCC 2007). Correspondingly, the sea level will fall when the climate gets colder due to volume reduction and water being bound in continental ice. During the latest glaciation, the global sea level was in the order of 120 m lower than at present (Fairbanks 1989). Sea level rise is not taking place evenly over the world and is affected by factors on different scales: global (gravitational fields), regional (isostatic rebound/subsidence) and local (precipitation and wind patterns). Examples of the effect of different factors acting on the local sea level for the Forsmark area in mid-Sweden are presented in Brydsten et al. (2009). Locally, sea-level changes determine the location of the shoreline and thus have a significant impact on future ecosystems.

6.6.3 Thresholding

Thresholding is the occurrence and location of thresholds that delimit water bodies in height. The threshold is affected by water level, landslides, human excavation, beaver dams and land-rise (the latter may alter the threshold due to tilting caused by uneven isostatic uplift) (Påsse 2001, Bergman et al. 2003). Humans have often affected the threshold in the past and have gained new farmland by lowering thresholds (e.g. Brunberg and Blomqvist 1998, 2001). Thresholding is of importance since it sets the boundary between lakes and the sea and determines lake geometry (volume, area, depth).

7 Process interactions in the biosphere

As stated in the introduction, an IM is a useful tool to systematically identify important processes in a system. In this chapter, SKB presents a general biosphere IM that is applicable to all kinds of ecosystems at the Forsmark site, and also other geographical locations with similar conditions. System component, represented by diagonal elements, may interact with each other by one or more processes. Depending on ecosystem and geographical location, process interactions may be more or less important for transport and accumulation of radionuclides. In this chapter, the significance of identified process interactions for transport and accumulation of radionuclides and for estimating the radiation exposure of man and other biota, is considered for an underground repository (> 30 m depth) at Forsmark.

7.1 The general biosphere interaction matrix

In Appendix A, the general biosphere IM produced at SKB is presented and in Table 7-1 the processes are listed together with where in the IM they are found. The IM has been developed with the methodology presented in Chapter 3. The IM is composed of 12 components (10 biosphere components and 2 boundary components shown on the lead diagonal), 50 processes (shown on the off diagonal) and 6 features (variables acting on and shown within the lead diagonal components and on processes).

The IM shown in Appendix A are an upgraded version from previous IM that has been produced by SKB and presented in Kautsky (2001), SKB (2001, 2010a), Aquilonius (2010), Andersson (2010) and Löfgren (2010). The major changes from previous interaction matrices are that diagonal elements are now reserved for physical components of the biosphere and that features are more explicitly shown. As an example, temperature, water composition, and radionuclide inventory were previously treated as components and shown on the lead diagonal in the IM, whereas they in this new version are treated as features and discussed within the process interaction. A detailed description of how the physical components affect each other through the different processes are described in detail in Section 7.2 and Appendix A.

Table 7-1. Processes in the biosphere IM with brief definitions. The processes are grouped into the following categories: 1) Biological processes, 2) Processes related to human behaviour, 3) Chemical, mechanical and physical processes, 4) Transport processes, 5) Thermal and radiological processes, and landscape development processes. * denotes processes that, although primarily associated with interactions involving non-human biota, may also involve humans. Full definitions are provided in Chapter 6. In the right column there is a reference to where in the IM (Appendix A) the processes are located.

Process	Definition	Interactions in the matrix (read row:column)	Numbering in SKB FEP data base
Biological processes			
Bioturbation	The mixing of elements and particles in both aquatic and terrestrial regolith by organisms.	6:2, 7:2, 8:2, 9:2, 10:2	Bio01
Consumption*	When organisms feed on solid material and/or on other organisms.	7:2, 7:4, 8:4, 8:6, 8:7, 8:8, 8:9, 8:10, 9:6, 10:7, 10:8, 10:9, 10:10, 10:11, 11:2, 11:6, 11:7, 11:8, 11:9, 11:10	Bio02
Death*	The generation of dead organic matter by organisms.	6:2, 6:4, 7:2, 7:4, 8:2, 8:4, 9:2, 9:4, 10:2, 10:4, 11:2, 11:4	Bio03
Decomposition	The breakdown of organic matter by organisms.	7:2, 7:3, 7:4	Bio04
Excretion*	The excretion of water or elements to the surrounding media by humans and other organisms.	6:3, 6:4, 6:5, 7:2, 7:3, 7:4, 7:5, 8:3, 8:4, 8:5, 9:2, 9:3, 9:4, 9:5, 10:2, 10:3, 10:4, 10:5, 11:2, 11:3, 11:4, 11:5	Bio05
Food supply	The fraction of produced biomass and particulate matter that can be used as a food source for humans and other organisms.	2:7, 2:11, 4:7, 4:8, 6:8, 6:9, 6:11, 7:8, 7:10, 7:11, 8:8, 8:10, 8:11, 9:8, 9:10, 9:11, 10:8, 10:10, 10:11, 11:10	Bio06
Growth*	The generation of biomass by organisms.	6:6, 7:7, 8:8, 9:9, 10:10, 11:11	Bio07

Process	Definition	Interactions in the matrix (read row:column)	Numbering in SKB FEP data base
Habitat supply	The providing of habitats for organisms by abiotic elements or other organisms.	2:6, 2:7, 2:8, 2:9, 2:10, 2:11, 3:6, 3:7, 4:6, 4:7, 4:8, 4:9, 4:10, 4:11, 6:6, 6:7, 6:8, 6:9, 8:6, 8:7	Bio08
Intrusion*	Non-human organisms or humans entering the repository, for example by locomotion, drilling or growth.	6:1, 7:1, 8:1, 9:1, 10:1, 11:1	Bio09
Material supply	The amount of material that is available for human utilisation for purposes other than feeding.	1:11, 2:11, 6:11, 7:11, 8:11, 9:11, 10:11	Bio10
Movement*	Animal locomotion in surface water.	7:4, 8:4, 9:4, 10:4, 11:4	Bio11
Particle release/trapping*	Organisms release particles (for example by fragmentation, spawning and pollen release) or trap particles.	6:4, 6:5, 7:4, 7:5, 8:4, 9:4, 9:5, 10:4, 10:5, 11:4	Bio12
Primary production	The fixation of carbon by primary producers in photosynthesis.	6:6	Bio13
Stimulation/inhibition*	When one biosphere component positively or negatively influences another biosphere component. The extreme of inhibition prevents settlement and leads to exclusion from the model area.	2:6, 2:7, 2:8, 2:9, 2:10, 2:11, 3:6, 3:7, 3:8, 3:9, 3:10, 3:11, 4:6, 4:7, 4:8, 4:9, 4:10, 4:11, 5:6, 5:7, 5:8, 5:9, 5:10, 5:11, 6:6, 6:7, 6:8, 6:9, 6:10, 6:11, 7:6, 7:7, 7:8, 7:9, 7:10, 7:11, 8:6, 8:7, 8:8, 8:9, 8:10, 8:11, 9:6, 9:7, 9:8, 9:9, 9:10, 9:11, 10:6, 10:7, 10:8, 10:9, 10:10, 10:11, 11:6, 11:7, 11:8, 11:9, 11:10, 11:11, 12:6, 12:7, 12:8, 12:9, 12:10, 12:11	Bio14
Uptake*	The incorporation of water or elements from the surrounding media into humans and other organisms.	6:3, 6:4, 6:5, 7:3, 7:4, 7:5, 8:3, 8:4, 8:5, 9:2, 9:3, 9:4, 9:5, 10:2, 10:3, 10:4, 10:5, 11:3, 11:4, 11:5	Bio15
Processes related to human behaviour			
Anthropogenic release	Release caused by humans of substances, water or energy into the local biosphere.	11:2, 11:3, 11:4, 11:5	Bio16
Material use	Human utilisation of the environment for purposes other than feeding.	11:1, 11:2, 11:6, 11:7, 11:8, 11:9, 11:10	Bio17
Species introduction/ extermination	Introduction or extermination of species from the model area by human activities. (e.g. introduction of crayfish in lakes).	11:6, 11:7, 11:8, 11:9, 11:10	Bio18
Water use	Water use by humans for purposes other than drinking, e.g. washing, irrigation and energy production.	11:3, 11:4	Bio19
Chemical, mechanical and physical processes			
Change of pressure	Pressure change in air or water above a surface.	2:2, 2:5, 3:1, 4:1, 4:4, 5:5	Bio20
Consolidation	Any process whereby loosely aggregated, soft, or liquid earth materials become firm and coherent rock or the compactation of regolith.	2:1, 2:2	Bio21
Element supply	The availability of elements and substances for use by organisms.	2:6, 2:7, 3:6, 3:7, 4:6, 4:7, 4:8, 4:9, 4:10, 5:6, 5:7, 5:8, 5:9, 5:10, 5:11	Bio22
Loading	Force caused by the weight of material that affects the underlying rock.	2:1, 4:1	Bio23
Phase transitions	Changes between different states of matter: solid, liquid and gas.	2:3, 2:4, 2:5, 3:2, 3:3, 3:5, 4:4, 4:5, 5:3, 5:4, 5:5	Bio24
Physical properties change	Changes in volume, density and/or viscosity.	2:2, 4:4	Bio25
Reactions	Chemical reactions excluding weathering, decomposition and photosynthesis.	2:3, 2:4, 2:5, 3:3, 4:4, 5:2, 5:5, 6:2, 6:3, 6:4, 6:5, 6:6, 7:2, 7:3, 7:4, 7:5, 8:2, 8:3,8:4, 9:2, 9:3, 9:4, 9:5, 10:2, 10:3, 10:4, 10:5, 11:5, 12:5	Bio26
Sorption/desorption	Dissolved substances adhere to surfaces or are released from surfaces.	2:3, 2:4, 3:2, 4:2, 4:4, 5:5, 6:3, 6:4, 6:5, 7:3, 7:4, 7:5, 8:2, 8:3, 8:4, 9:2, 9:3, 9:4, 9:5, 10:2, 10:3, 10:4, 10:5, 11:2, 11:4, 11:5	Bio27
Water supply	The amount of water available for humans and other organisms for drinking and other uses, e.g. irrigation.	1:11, 3:6, 3:7, 3:8, 3:9, 3:10, 3:11, 4:6, 4:7, 4:8, 4:9, 4:10, 4:11	Bio28
Weathering	Disintegration of solid matter into smaller pieces.	1:2, 2:2, 3:1, 3:2, 4:1, 4:2	Bio29

Process	Definition	Interactions in the matrix (read row:column)	Numbering in SKB FEP data base
Wind stress	A mechanical force generated by wind affecting the biosphere.	5:4	Bio30
Transport processes			
Acceleration	The change in velocity of a fluid or body over time and/or the rate and direction of velocity change. May be either positive or negative (retardation).	2:4, 2:5, 6:4, 6:5, 7:4, 8:4, 9:4, 11:4, 11:5	Bio31
Convection	The transport of a substance or a conserved property with a fluid or gas.	1:2, 1:3, 1:4, 1:5, 2:1, 2:3, 3:1, 3:3, 3:4, 4:1, 4:3, 4:4, 5:1, 5:3, 5:4, 5:5, 6:2, 6:3, 6:4, 7:2, 7:3, 8:2, 8:3, 9:2, 9:3, 10:2, 10:3, 11:2, 11:3, 11:5, 12:4	Bio32
Covering	The covering of surface water by e.g. vegetation or ice that reduces light penetration and prevents the exchange of gases and particles between the water and the atmosphere.	4:5, 6:4, 6:5, 11:4	Bio33
Deposition	Vertical transfer of a material or element to a surface of any kind due to gravitation, e.g. sedimentation, rainfall, and snowfall.	4:2, 5:2, 5:4, 5:11	Bio34
Export	Transport out of the model area.	2:12, 3:12, 4:12, 5:12, 6:12, 7:12, 8:12, 9:12, 10:12, 11:12	Bio35
Import	Transport into the model area.	4:12, 12:2, 12:3, 12:4, 12:5, 12:6, 12:7, 12:8, 12:9, 12:10, 12:11	Bio36
Interception	The amount of precipitation that does not reach the ground but is retained on vegetation.	6:4	Bio37
Relocation	The horizontal transport of solid matter and sessile organisms from one point to another.	2:2, 2:6, 3:2, 4:2, 4:5, 4:6, 4:7, 4:8, 4:9, 4:10, 5:2, 5:6, 11:2	Bio38
Resuspension	The stirring up of previously settled particles in water or air.	2:4, 2:5, 4:2, 4:5, 5:2	Bio39
Saturation	Water content that affects physical and chemical properties of the regolith	3:2, 4:2, 12:3	Bio40
Radiological and thermal processes			
Radioactive decay	The physical transformation of radionuclides to other radionuclides or stable isotopes.	2:2, 2:5, 3:3, 3:5, 4:4, 5:5, 6:6, 7:7, 8:8, 9:9, 10:10, 11:11	Bio41
Exposure	The act or condition of being subject to irradiation. Exposure can either be external exposure from sources outside the body or internal exposure from sources inside the body.	2:6, 2:7, 2:8, 2:9, 2:10, 2:11, 3:6, 3:7, 3:8, 3:9, 3:10, 3:11, 4:6, 4:7, 4:8, 4:9, 4:10, 4:11, 5:6, 5:7, 5:8, 5:9, 5:10, 5:11, 6:6, 7:7, 8:8, 9:9, 10:10, 11:11	Bio42
Heat storage	The storage of heat in solids and water.	2:2, 3:3, 4:4, 5:5	Bio43
Irradiation	The process whereby an object is exposed to ionising radiation and absorbs energy.	2:2	Bio44
Light related processes	Processes related to the light entering the biosphere (insolation), e.g. absorption, attenuation, reflection and scattering.	2:2, 2:6, 4:4, 4:6, 5:5, 6:2, 6:3, 6:4, 6:5, 6:6, 7:2, 7:3, 7:4, 7:5, 8:2, 8:3, 8:4, 9:2, 9:3, 9:4, 9:5, 10:2, 10:3, 10:4, 10:5, 11:5, 12:2, 12:3, 12:4, 12:5, 12:6	Bio45
Radiolysis	The disintegration of molecules caused by radionuclide decay.	3:3, 4:4	Bio46
Radionuclide release	Release of radionuclides from the repository.	1:1	Bio47
Landscape development processes			
Change in rock surface location	Changes in the location of the rock surface due to isostatic rebound or repository induced changes.	1:2, 12:1, 12:2	Bio48
Sea-level change	Alteration in the level of the sea relative to the land.	12:4	Bio49
Thresholding	The occurrence and location of thresholds delimits lakes and sea basins.	2:3, 2:4, 2:12	Bio50

7.2 Process interactions between physical components in the biosphere

System components represented diagonal elements, may interact with each other by one or more processes. Some processes occur in many places in the IM. Below, each box in the IM is described separately to fully illustrate by which processes each diagonal component interacts with the other diagonal elements. Processes whereby diagonal components interact are presented in alphabetical order, i.e. they are not listed by importance in the safety assessment. Although a process may be important for a safety assessment in the interaction between two diagonal elements, it may be insignificant for the assessment in the interaction between two other diagonal elements. The significance of a process for a safety assessment for a repository at Forsmark is considered for each interaction at which a process is identified (Appendix A). The importance of each process interaction is discussed below and processes identified as needing to be considered are shown in Appendix B. Processes that are identified as needing to be considered in at least one process interaction are summarised in Chapter 8.

1:1 Geosphere is a diagonal element (further described in Chapter 4). The geosphere is situated at the boundary of the biosphere matrix and processes by which the geosphere affects the geosphere are not described in this report. Neither are the internal processes or interactions between features and processes in the geosphere discussed in length. Thus, the feautres and geosphere are only described in relation to interactions with true biosphere components. Internal process within the geosphere relevant for to biosphere matrix are a) Radionuclide release

a) Radionuclide release – Transport of radionuclides and toxicants in water and gas phase from the repository into the geosphere will affect the amount of these in the geosphere and biosphere and this interaction needs to be considered in a safety assessment. For the biosphere, the important flux is the upward, i.e. from geosphere to biosphere.

1:2 Geosphere affects **regolith** by the processes a) Change in rock surface location, b) Convection, and c) Weathering.

a) Change in rock surface location – Local changes in rock surface location may be caused by e.g. collapse of caverns resulting in cave-in of the surrounding rock. Other examples could be neotectonic movements (Lagerbäck et al. 2005). This affects the stress conditions in the surrounding rock and may affect the height of the regolith. However, large scale earthquackes are not expected in Forsmark and the repository are situated between 50 and 120 meters depth. Thus, cavern collapse is not expected and would be attenuated at the surface. Therefore, other processes affecting regolith are more important for the topography and this interaction is not important to consider in a safety assessment for a repository at Forsmark.

b) Convection – The geosphere affect the regolith mainly through the flow of elements and water (discussed in 1:3 and 1:4) but also flows of heat occur. However, temperature within water in regolith, surface waters, and solar insolation mainly determine the temperature in the regolith waters and the geosphere has a minor effect on the temperature in the regolith. Thus, this interaction is not important to consider in a safety assessment for a repository at Forsmark.

c) Weathering – Weathering of a solid rock (geosphere) may form regolith. However, weathering of the solid rock has a minor influence on the formation of regolith compared with other regolith formation processes (e.g. peat formation and sedimentation) and, therefore, this interaction is not important to consider in a safety assessment for a repository at Forsmark.

1:3 Geosphere affects water in regolith by the process a) Convection.

a) Convection – Transport of radionuclides and toxicants in water and the gas phase from the geosphere will affect the amount of these in the geosphere and biosphere and this interaction needs to be considered in a safety assessment for an underground repository at Forsmark. For the biosphere, the important flux is upward, i.e. from geosphere to biosphere.

1:4 Geosphere affects surface water by the process a) Convection.

a) Convection – Transport of radionuclides and toxicants in water and the gas phase from the geosphere will affect the amount of these in the geosphere and biosphere and this interaction needs to be considered in a safety assessment for a repository at Forsmark.

1:5 Geosphere affects gas and local atmosphere by the process a) Convection.

a) Convection – Transport of radionuclides and toxicants in water and the gas phase from the geosphere will affect the amount and composition of gas in the geosphere and biosphere. The transport of gas from the geosphere is normally of little significance in comparison to gas content in e.g. regolith (i.e. elements in the gas phase entering the gas phase of the regolith would be very diluted in the regolith gas phase). However, gas transport of e.g. H_2, CO_2, CH_4, Rn and SO_2 and H-3 and C-14 labelled variants of some of these gases from a repository may be important and this interaction needs to be considered in a safety assessment for a repository at Forsmark.

1:6 There are no processes by which the **Geosphere** affects **primary producers** that are relevant to include in a safety assessment for a repository at Forsmark.

1:7 There are no processes whereby the **Geosphere** affects **decomposers** that are relevant to include in a safety assessment for a repository at Forsmark.

1:8 There are no processes whereby the **Geosphere** affects **filter feeders** that are relevant to include in a safety assessment for a repository at Forsmark.

1:9 There are no processes whereby the **Geosphere** affects **herbivores** that are relevant to include in a safety assessment for a repository at Forsmark.

1:10 There are no processes whereby the **Geosphere** affects **carnivores** that are relevant to include in a safety assessment for a repository at Forsmark.

1:11 Geosphere affects **humans** by the processes a) Material supply, and b) Water supply.

a) Material supply – The bedrock can be utilised for various purposes. For example, mineral resources can be extracted and used by humans and, the rock itself can be used as a material to store thermal energy. These activities may influence the location of human settlements. The Forsmark site is underlain by granitic rocks and can be described as sterile from an ore viewpoint (Lindroos et al. 2004). There are no deposits of industrial minerals or commercial stone in the area. An area south of the Forsmark area has a small ore potential for iron, however the type of ore is of no mining interest and compared with central parts of Bergslagen, the Forsmark area's ore potential is insignificant. These types of possible future human actions need to be discussed in Future Human Action assessment of a safety assessment but are not important to consider in the biosphere part of a safety assessment for a repository at Forsmark.

b) Water supply – Water can be extracted by humans from the geosphere by drilled wells. Supply of water influence the location of human settlements. The number of people living in the area will affect the demand for water but the availability of water can also have an influence on human use of water e.g. showering and/or bathing. If water is limiting, water supply may affect the number of people living in an area and the transport of radionuclides to humans. Therefore, this interaction needs to be considered in a safety assessment for a repository at Forsmark.

1:12 There are no processes by which **geosphere** affects **external conditions** that are relevant to include in the biosphere part of a safety assessment for a repository at Forsmark.

2:1 Regolith affects **the geosphere** by the processes a) Consolidation, b) Convection, and c) Loading.

a) Consolidation – The transformation of regolith to solid rock is a slow process that implies a gradual reduction in volume and increase in density in response to increased load or compressive stress. This process is affected by the weight of regolith (thickness and density). However, the likely degree of consolidation would be very limited under present-day conditions and thus does not need to be considered in a safety assessment for a repository at Forsmark

b) Convection – Heat transport from the biosphere to the geosphere may affect the temperature in the geosphere. Water composition of water in the regolith and surface waters infiltrating the geosphere may influence the composition of the groundwater. The water composition infiltrating the rock affects the composition in the rock. This is the reason why the salinity changes in the rock. Flux of heat is important to consider in other parts of a safety assessment (i.e. geosphere and near field) since permafrost conditions may lead to freezing temperatures in the geosphere and repository. However, the flux of heat to geosphere is assumed not to influence the biosphere conditions and this interaction is not important to consider in the biosphere part of a safety assessment for a repository at Forsmark.

c) Loading – The thickness of the regolith affects the stress on the geosphere. The depth of regolith is relatively small in the Forsmark area (Hedenström and Sohlenius 2008, Sohlenius et al. 2013) and should have a minor impact on the mechanical stress on the geosphere and, therefore, is not important to be considered in a safety assessment for a repository at Forsmark.

2:2 Regolith is a diagonal element that is further described in Chapter 4. The regolith is internally affected by the features Geometry, Material composition, Temperature, Water composition, Stage of succession and Radionuclide inventory. The processes by which the properties and features of the regolith affect the regolith are: a) Change of pressure, b) Consolidation, c) Heat storage, d) Irradiation, e) Light-related properties, f) Physical properties change, g) Radioactive decay, h) Relocation, and i) Weathering.

a) Change of pressure – in terrestrial ecosystems the topography of the regolith affects the pressure which may lead to heating or cooling, so called adiabatic temperature changes. However, the Forsmark area will always be coastal and will not be associated with any large changes in topography (as would be the case in e.g. mountain areas) and therefore this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

b) Consolidation – Regolith layers may be compacted and thereby the depth of the regolith layers is altered. There are few natural processes whereby compactation will have a large effect on the regolith layers, but draining of wetlands to gain agricultural land may have a significant effect on the regolith depths. This needs to be considered in a safety assessment for a repository if draining and utilisation of wetlands for agricultural land are deemed to be an exposure pathway for humans.

c) Heat storage – The density, composition and grain size of regolith together with its thermal properties determine the amount of heat that can be stored in a given volume of regolith per unit of temperature change. Generally, the heat storage of water is of greater importance for the temperature in the biosphere and this interaction is not important to consider in a safety assessment for a repository at Forsmark.

d) Irradiation – Irradiation of material in the regolith by radionuclides in the materials and in the water may affect the mineralogical structure of the material. However the amount of radionuclides is generally too small to have any significant effect on the regolith and therefore does not need to be considered in a safety assessment for a repository at Forsmark.

e) Light-related processes – The reflection properties of the regolith influence the amount of sunlight absorbed and thereby the temperature in the regolith in terrestrial areas. However, global climate is more important than the reflection properties of the regolith in determining the temperature of the regolith. In aquatic ecosystems, the regolith is always covered with water and the major part of the adsorption takes place in the water column. Thus, this interaction is not important to consider in a safety assessment for a repository at Forsmark.

f) Physical properties change – The temperature of the regolith can affect the volume of the components of the regolith by e.g. freezing. However, the temperature range in regolith in the aquatic systems is relatively narrow due to the isolating effect of the water body and freezing of the regolith is not assumed to occur in an interglacial period. Under glacial conditions, the regolith in a lake may freeze, but humans are assumed only to utilize marine ecosystems at glacial conditions. Thus this interaction does not need to be considered in the aquatic part of the radionuclide model. In terrestrial ecosystems, the effect may be larger with effects on hydrological transport, which suggests the need for separate hydrological modelling during periglacial conditions. Under periglacial conditions, cryoturbation may be an important process by which soil is turbated (Löfgren 2010).

g) Radioactive decay – Radionuclides in the different biosphere components undergo radioactive decay whereby they transform into other radionuclides or stable isotopes. Decay of radionuclides is important to consider in estimating the amounts of different radionuclides in the biosphere and this process needs to be considered in a safety assessment for a repository at Forsmark.

h) Relocation – The inclination and the topography of the land (i.e. the feature geometry) influence the possibility for, and the extent of, relocation of materials e.g. via resuspension and landslides. However, the low relief in Forsmark suggests that this would be a rare phenomenon on short time scales and does not need to be considered in a safety assessment for a repository at Forsmark. So although the relocation of regolith may be important for the distribution of radionuclides in the landscape this interaction is not important since the major effect on relocation of regolith is due to shoreline displacement treated in interaction 12:2 and erosion treated in interactions 4:2 and 5:2.

i) Weathering – Freezing of regolith (i.e. the feature Temperature) may cause weathering of the regolith. In aquatic ecosystems, the temperature range in the regolith is relatively narrow due to the isolating effect of the water body and freezing of the regolith is not assumed to occur in an interglacial period. Thus, this interaction does not need to be considered in the aquatic part of the radionuclide model. For terrestrial ecosystems, weathering may have larger effect and influence the composition of the remaining regolith. Thus, this interaction needs to be considered for terrestrial ecosystems in a safety assessment for a repository at Forsmark.

2:3 Regolith affects **water in regolith** by the processes a) Convection, b) Phase transitions, c) Reactions, d) Sorption/desorption, and e) Thresholding.

a) Convection – The magnitude and distribution of the water flow in the regolith is influenced by the hydraulic conductivity and storage capacity (porosity) of the regolith as well as the topography. This is an important process to consider in a safety assessment for a repository at Forsmark.

b) Phase transitions – Regolith may affect water composition by leaching (in which minerals attached to solids are solubilised from the regolith and released to the water). The location of and chemical composition of the regolith and the mineralogy of rock surfaces thereby influence the chemical composition of the water. The rate of leaching of non-radioactive elements is not important for the safety assessment but the net result, i.e. concentrations of elements in the water, may be of importance. However, other factors are assumed to be of greater importance for water chemistry and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

c) Reactions – Elements in the regolith may be altered due to chemical reactions such as redox changes (oxidation) and elements may thereby be released to the water and influence the water composition. Reactions may lead to dissolution of natural radionuclides and toxicants in minerals in regolith to the water phase. Transformation of crystal water in minerals in regolith to “free” water may affect the amount of water in the regolith. Other factors (such as precipitation, discharge, and large scale water flow in the landscape) are assumed to have greater influence on the water content. However, the effect of reactions in the regolith on water chemistry may have large effect on concentrations in both regolith and pore water (e.g. due to calcite leaching in Forsmark) and this interaction need to be considered in a safety assessment for a repository at Forsmark.

d) Sorption/desorption – The composition and grain size (available surfaces for sorption) of the regolith will affect the extent of sorption of radionuclides and thereby the distribution of radionuclides between regolith and water. The degree of sorption of radioactive elements is important for transport and accumulation of radionuclides and thus needs to be considered in a safety assessment for a repository at Forsmark.

e) Thresholding – The regolith determines the location of thresholds and thereby influences the water in regolith. Thresholds are important for the development of the landscape and this interaction needs to be considered in a safety assessment for a repository at Forsmark.

2:4 Regolith affects **surface water** by the processes a) Acceleration, b) Phase transitions, c) Reactions, d) Resuspension, e) Sorption/desorption, and f) Thresholding.

a) Acceleration – In aquatic ecosystems the bottom topography (i.e. bathymetry) determines the water depth and influences thereby the height of the waves. In addition, the fetch (the distance over which the blowing wind is not disturbed) influences wave formation e.g. with sheltered areas occurring behind islands. Water turnover and wind velocities above lake/marine basins may affect transport and accumulation of radionuclides, but factors other than regolith are assumed to have larger effect on the water turnover and wind velocities and thus this interaction is not important to consider in a safety assessment for a repository at Forsmark.

b) Phase transitions – Regolith may affect water composition by leaching (in which minerals attached to solids are solubilised from the regolith and released to the water). The location of and chemical composition of the regolith and the mineralogy of rock surfaces thereby influence the chemical composition of the water. The rate of leaching of non-radioactive elements is not important for the radionuclide modelling, but the net result, i.e. concentrations of elements in the water, may be of importance. However, other factors are assumed to be of greater importance for water chemistry and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

c) Reactions – Elements in the regolith may be altered due to chemical reactions such as redox changes (oxidation) and elements may thereby be released to the water and influence the water composition. Reactions may lead to dissolution of natural radionuclides and toxicants in minerals in regolith to the water phase. Other factors are assumed to have greater influence on the water chemistry and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

d) Resuspension – The size distribution of the particles in the regolith influences the amount of material resuspended in the water and thereby the content of particulate matter in the water. Resuspension is an important route of transfer of particles from sediments to water and needs to be considered in a safety assessment for a repository at Forsmark.

e) Sorption/desorption – The composition and grain size (available surfaces for sorption) of the regolith will affect the extent of sorption of radionuclides and thereby the distribution of radionuclides (and other elements) between regolith and water. The degree of sorption of radioactive elements is important for transport and accumulation of radionuclides and thus needs to be considered in a safety assessment for a repository at Forsmark.

f) Thresholding – Thresholding includes all processes that affect the occurrence and location of thresholds that delimit water bodies in height. Thresholds are important for the development of the landscape and this interaction needs to be considered in a safety assessment for a repository at Forsmark.

2:5 Regolith affects **gas and local atmosphere** by the processes a) Acceleration, b) Change of pressure, c) Phase transitions, d) Radioactive decay, e) Reactions, and f) Resuspension.

a) Acceleration – The topography results in increases and decreases in the wind flow and influence thereby the distribution of the wind velocities and directions. No large topography changes are expected in Forsmark and thus no changes in wind velocities compared to present-day conditions are expected and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

b) Change of pressure – The topography influences the air pressure at the surface. However, with the flat topography at Forsmark, there will not be large pressure changes at the surface. Thus, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

c) Phase transitions – The regolith may affect the concentration of dissolved radionuclides by dissolution to the gas phase of natural radionuclides included in minerals in the regolith. In comparison with other processes, this process commonly involves very small amounts of radionuclides, and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

d) Radioactive decay – Decay of some radionuclides in water forms elements in the gas phase, e.g. Ra decaying to Rn, and thereafter they can readily be transported via gas. Radon is an example of a gas that can penetrate buildings and in some cases accumulate in areas with deficient ventilation. This interaction needs to be considered in a safety assessment for a repository at Forsmark.

e) Reactions – Elements in the regolith may react with elements in the gas phase in the regolith. The amounts of gases in the regolith in aquatic and terrestrial systems are most often small and are not considered to be severely affected by elements in the regolith. Therefore the transport and accumulation of radionuclides are not significantly influenced. This interaction therefore does not need to be considered in a safety assessment for a repository at Forsmark.

f) Resuspension – The size distribution of the grains in the regolith influences the amount of material resuspended in the air and thereby the particulate content in the air. Resuspension of particles is important for forming dust in air and needs to be considered in a safety assessment for a repository at Forsmark.

2:6 Regolith affects **primary producers** by the processes a) Element supply, b) Exposure, c) Habitat supply, d) Light-related processes, e) Relocation, and f) Stimulation/inhibition.

a) Element supply – Microalgae living in the sediments and rooted aquatic vegetation acquire some of their nutrient supply from the regolith. This is also true for terrestrial primary producers. Accordingly, this interaction might constitute a route of transport of radionuclides from regolith to biota and the interaction needs to be considered in a safety assessment for a repository at Forsmark.

b) Exposure – Exposure can either be external due to sources outside the body or internal due to sources inside the body. Concentration, location and type of radionuclides in surface waters, groundwater, regolith, and in the atmosphere, i.e. in all parts of the biosphere system, affect the external exposure of, and thus the radiologic and toxic effects on, biota. This interaction needs to be considered in a safety assessment for a repository at Forsmark.

c) Habitat supply – The regolith is one of several important factors for the settlement of primary producers, as primary producers are often dependent on the substrate (e.g. in aquatic ecosystems hard vs. soft bottoms, in terrestrial ecosystems coarse vs. fine-grained regolith). This interaction needs to be considered in a safety assessment for a repository at Forsmark, since the occurrence of biota is important for transfer and accumulation of radionuclides.

d) Light-related processes – the topography of the sediments may shade primary producers and thereby influence primary production. This interaction is assumed to be less important than effects of e.g. water depth, transparency, and element supply. Therefore this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

e) Relocation – Relocated regolith may deposit on primary producers and this might affect their production and biomass. Sedimentation is important for the transfer of radionuclides between water and sediment, and relocation is important to consider for determining where deposits will be found in the landscape. In agricultural land ploughing occurs regularly, causing a complete mixing and aeration of the affected regolith layer. However, although mixing and aeration of regolith needs to be considered, the direct effects of relocation such as deposition on primary producers is not important to consider in a safety assessment for a repository at Forsmark.

f) Stimulation/inhibition – Chemical composition and temperature of the regolith may influence the pattern of settlement, as different species thrive at different temperatures. Moreover, the temperature will affect the metabolism and types of biota and that may be important for distribution of radionuclides in the biotic community and exposure of man. Therefore this interaction needs to be considered in a safety assessment for a repository at Forsmark.

2:7 Regolith affects **decomposers** by the processes a) Element supply, b) Exposure, c) Food supply, d) Habitat supply, and e) Stimulation and inhibition.

a) Element supply – Bacteria present within the sediment and soil take up elements directly from the sediment and thereby the regolith supplies elements to decomposers. This may be an important pathway for radionuclide transport from sediments into biota and thus this interaction needs to be considered in a safety assessment for a repository at Forsmark.

b) Exposure – Exposure can either be external due to sources outside the body or internal due to sources inside the body. Concentration, location and type of radionuclides in surface waters, groundwater, regolith, and in the atmosphere, i.e. in all parts of the biosphere system, affect the external exposure of, and the radiologic and toxic effects on, biota. The effects on organisms may include cellular death and affect biomass of decomposers, and this interaction needs to be considered in a safety assessment for a repository at Forsmark.

c) Food supply – Regolith can be used as a food source by decomposers. This may be an important pathway for radionuclide transport from sediments/soils into biota and thus this interaction needs to be considered in a safety assessment for a repository at Forsmark.

d) Habitat supply – Regolith is important for the settlement of decomposers, as they are often dependent on a certain kind of substrate. Habitat distribution differentiates, in aquatic ecosystems, between hard bottoms and soft bottoms, and in terrestrial ecosystems between coarse and fine-grained regolith. This interaction needs to be considered in a safety assessment for a repository at Forsmark since the occurrence of biota is important for transfer and accumulation of radionuclides.

e) Stimulation/inhibition – Chemical composition and temperature of the regolith may influence the pattern of settlement as different species thrive at different temperatures. Moreover, the temperature will affect the metabolism and types of biota and that may be important for distribution of radionuclides in the biotic community and exposure of man. Therefore, this interaction needs to be considered in a safety assessment for a repository at Forsmark.

2:8 Regolith affects **filter feeders** by the processes a) Exposure, b) Habitat supply, and c) Stimulation/inhibition.

a) Exposure – Exposure can either be external due to sources outside the body or internal due to sources inside the body. Concentration, location and type of radionuclides in surface waters, groundwater, regolith, and in the atmosphere, i.e. in all parts of the biosphere system, affect the external exposure of, and the radiologic and toxic effects on, biota. This interaction needs to be considered in a safety assessment for a repository at Forsmark.

b) Habitat supply – Filter feeders occur only in aquatic ecosystems. Regolith is important for the settlement of filter feeders as they are often dependent on the substrate. Some species thrive on hard bottoms (e.g. in limnic ecosystems *Dreissena polymorpha* and in marine ecosystems *Mytilus edulis*) and others thrive on soft bottoms (e.g. in limnic ecosystems *Anodonta anatine* and in marine *Macoma baltica*). Hence, for aquatic ecosystems, this interaction needs to be considered in a safety assessment for a repository at Forsmark, since the occurrence of biota is important for transfer and accumulation of radionuclides.

c) Stimulation/inhibition – Chemical composition and temperature of the regolith may influence the pattern of settlement as different species thrive at different temperatures. Moreover, the temperature will affect the metabolism and type of biota and that may be important for the distribution of radionuclides in the biotic community and exposure of man. Therefore this interaction needs to be considered in a safety assessment for a repository at Forsmark.

2:9 Regolith affects **herbivores** by the processes a) Exposure, b) Habitat supply, and c) Stimulation/inhibition.

a) Exposure – Exposure can either be external due to sources outside the body or internal due to sources inside the body. Concentration, location and type of radionuclides in surface waters, groundwater, regolith, and in the atmosphere, i.e. in all parts of the biosphere system, affect the external exposure of, and the radiologic and toxic effects on, biota. This interaction needs to be considered in a safety assessment for a repository at Forsmark.

b) Habitat supply – The settlement of herbivores is mainly determined by the availability of primary producers. However, the regolith may be important for e.g. nests and therefore, the effect of regolith on the settlement of herbivores needs to be considered in a safety assessment for a repository at Forsmark.

c) Stimulation/inhibition – Chemical composition and temperature of the regolith may influence the pattern of settlement, as different species thrive at different temperatures. Moreover, the temperature will affect the metabolism and type of biota and that may be important for distribution of radionuclides in the biotic community and exposure of man. Therefore, this interaction needs to be considered in a safety assessment for a repository at Forsmark.

2:10 Regolith affects **carnivores** by the processes a) Exposure, b) Habitat supply, and c) Stimulation/inhibition.

a) Exposure – Exposure can either be external due to sources outside the body or internal due to sources inside the body. Concentration, location and type of radionuclides in surface waters, groundwater, regolith, and in the atmosphere, i.e. in all parts of the biosphere system, affect the external exposure of, and the radiologic and toxic effects on, biota. This interaction needs to be considered in a safety assessment for a repository at Forsmark.

b) Habitat supply – Abundances of carnivores are more dependent on prey than regolith. However, the regolith may be important for e.g. nests and therefore, the effect of regolith on the settlement of carnivores needs to be considered in a safety assessment for a repository at Forsmark.

c) Stimulation/inhibition – Chemical composition and temperature of the regolith may influence the pattern of settlement, as different species thrive at different temperatures. Moreover, the temperature will affect the metabolism and type of biota and that may be important for the distribution of radionuclides in the biotic community and exposure of man. Therefore, this interaction needs to be considered in a safety assessment for a repository at Forsmark.

2:11 Regolith affects **humans** by the processes a) Exposure, b) Food supply, c) Habitat supply, d) Material supply and e) Stimulation/inhibition.

a) Exposure – Exposure can either be external due to sources outside the body or internal due to sources inside the body. Concentration, location and type of radionuclides in surface waters, groundwater, regolith, and in the atmosphere, i.e. in all parts of the biosphere system, affect the external exposure of, and the radiologic and toxic effects on, humans. This interaction needs to be considered in a safety assessment for a repository at Forsmark.

b) Food supply – Regolith may be consumed accidentally with food or on purpose, e.g. by children. The deliberate ingestion of soil by adults is a recognised medical condition, known as pica, which tends to last for a relatively short time. Inadvertent ingestion of soil does not normally need to be considered (SKB 2014c). Nevertheless, soils adhered to the surface of e.g. carrots and potatoes may be ingested and the amount adhered to surfaces is often incorporated in studies of concentration ratios. Thus, although it most likely has small effect on dose, this interaction should be considered in a safety assessment for a repository at Forsmark.

c) Habitat supply – Human settlement is mainly determined by the area, soil type, and the type of ecosystem. Thus, the stage of succession of the regolith (lake, wetland, forest) affects the demographics in the area. Thus, this interaction needs to be considered in a safety assessment for a repository at Forsmark. Moreover, the composition of the regolith determines whether agriculture is possible (see Stimulation/inhibition below).

d) Material supply – Humans may use regolith as material supply e.g. sand in concrete for buildings or peat used for generating heat. The effect of this interaction should be considered in a safety assessment for a repository at Forsmark.

e) Stimulation/inhibition – The chemical composition of the regolith may influence the settlement of humans and affect their possibility to use the land for agricultural purposes and affect the harvest, i.e. a good soil composition may result in agriculture and a high food yield, whereas poorer soils may result in less food or no agriculture at all. This interaction needs to be considered in a safety assessment for a repository at Forsmark.

2:12 Regolith affects **external conditions** by the processes a) Export, and b) Thresholding.

a) Export – The main exports of material from the ecosystems are water and particles, whereas export of regolith is minor. Thus, the export of radionuclides out of the system via export of regolith should be minor and have minor effects on the receiving environment (i.e. external conditions) and this interaction does not need to be considered a safety assessment for a repository at Forsmark.

b) Thresholding – Regolith determines the location of thresholds and thresholds influence the external conditions as they determine the functioning of the landscape (lakes, land, and wetlands). Thresholds are important for the development of the landscape and this interaction needs to be considered in a safety assessment for a repository at Forsmark.

3:1 Water in regolith affects **geosphere** by the processes a) Change of pressure, b) Convection, and c) Weathering.

a) Change of pressure – Change of pressure affects the pore water pressure in the rock. However, there should be minor changes in pressure over time and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

b) Convection – The hydrology in the regolith influences the recharge and discharge of groundwater and thereby the hydrology in the geosphere and the composition of groundwater. This interaction may be important for the transport of radionuclides and needs to be considered in a safety assessment for a repository at Forsmark.

c) Weathering – The water flow in the regolith influences the weathering of rock. Weathering will have a minor effect on the transport and accumulation of radionuclides originating from the repository, and does not need to be considered in a safety assessment for a repository at Forsmark.

3:2 Water in regolith affects **regolith** by the processes a) Phase transitions, b) Relocation, c) Saturation, d) Sorption/desorption, and e) Weathering.

a) Phase transitions – The composition of the water in the regolith will affect chemical precipitation and dissolution reactions (i.e. phase transitions). This will influence the material composition, geometry and porosity of the regolith. The physical structure of the regolith is assumed to be a result of this interaction. Since the structure of the regolith is important for the transport and accumulation of radionuclides this interaction needs to be considered in a safety assessment for a repository at Forsmark.

b) Relocation – Water in the regolith might affect the regolith by relocating it to another place. Temperature changes in the water may lead to freezing of the water and expansion of the ice and/or freeze and thaw in the regolith may result in the formation of so called pingos thereby changing the topography, e.g. formation of hills in bog lands. Other components (e.g. surface water) are assumed to affect the relocation of regolith to a larger degree and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

c) Saturation – The magnitude and direction of the water flow influences the water content in the regolith. In aquatic ecosystems and in the terrestrial mire ecosystem, the regolith is saturated with water for the main part of the year and this interaction does not need to be considered. However, in agricultural ecosystems, saturation may determine the need for irrigation which may be an important pathway for radionuclides. Thus, this interaction needs to be considered in a safety assessment for a repository at Forsmark.

d) Sorption/desorption – The composition and grain size (available surfaces for sorption) of the regolith and the composition of the water in regolith will affect the extent of sorption of radionuclides and thereby the distribution of radionuclides between regolith and water. The degree of sorption of radioactive elements is important for transport and accumulation of radionuclides and thus needs to be considered in a safety assessment for a repository at Forsmark.

e) Weathering – The composition of water (i.e. the feature Water composition) in the regolith influences the weathering of the regolith. For example, the PH affects the amount of weathering. However, other factors are assumed to have larger effect on the regolith and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

3:3 Water in regolith is a diagonal element defined as the water component in regolith, further described in Chapter 4. Water in regolith is internally affected by the features Geometry, Material composition, Stage of succession, Temperature, Water composition and Radionuclide inventory. The processes by which the properties and features of the water in regolith affect itself are: a) Convection, b) Heat storage, c) Phase transitions, d) Radioactive decay, e) Radiolysis, and f) Reactions.

a) Convection – The composition of the water in the regolith will affect the density and viscosity of the water which in turn will affect the magnitude, distribution and direction of water flow in the regolith. The water content, magnitude, direction and distribution of water flow in the regolith will in turn affect the heat transport in the regolith. Convection of heat in water in regolith does not need to be considered in a safety assessment, but water flow in the regolith (affected by the water composition) is important for the transport of radionuclides and thus this interaction needs to be considered in a safety assessment for a repository at Forsmark.

b) Heat storage – The water content as well as the magnitude, direction and distribution of water flow in the regolith affect the heat storage capacity and thus the temperature in the regolith. The heat storage of surface water is of greater importance for the temperature in the biosphere and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

c) Phase transitions – The water composition in the different parts of the biosphere system may affect the dissolution/precipitation of radionuclides and thus the distribution of radionuclides between the water in regolith and the regolith component. Radionuclides are assumed to be dissolved in water in order to be transported to the biosphere and thus dissolution/precipitation does not need to be considered in a safety assessment for a repository at Forsmark. The temperature also affects the state of the water in the regolith (frozen or liquid). In terrestrial ecosystems, ground frost is a common feature during the winter period. Freezing of water in the regolith prevents transport and during permafrost transport of radionuclides may be prevented from transport or redistributed relative to their distribution during antecedent temperate conditions. Thus, this interaction needs to be considered in a safety assessment for a repository at Forsmark.

d) Radioactive decay – Radionuclides in the different biosphere components undergo radioactive decay where they transform into other radionuclides or form stable isotopes. Decay of radionuclides is important to consider in estimating the amounts of different radionuclides in the biosphere and this process needs to be considered in a safety assessment for a repository at Forsmark. The build-up of stable isotopes due to radioactive decay may also affect the composition of the water. However, the amounts of radionuclides from a repository are too small to have any significant effect on the water composition and that aspect of decay does not need to be considered.

e) Radiolysis – Radiation from decaying radionuclides may cause radiolytic decomposition of the water and thereby affecting the water composition in the different components of the biosphere system. However, amounts of radionuclides from a repository will be too small to have any significant effect on water composition and thus this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

f) Reactions – Reactions within water in regolith may affect the composition and temperature of the water. Reactions of water may change the form of different elements. For example, C-14 can occur in many forms of which some are easily utilised by plants (carbon dioxide) whereas others are not (methane). By reactions, methane can transform to CO_2 which of course then has a large effect on the bioavailability of any C-14 initially present as methane. Reactions are dependent on water composition (e.g.in the case of methane and carbon dioxide the availability of oxygen) and on temperature. The reactions can require heat or release heat and thereby influence the temperature of water in regolith. However, other factors (such as insolation) are assumed to have a greater influence on temperature. However, the effects of reactions in water on the composition of the water need to be considered in a safety assessment for a repository at Forsmark.

3:4 Water in regolith affects **surface water** by the process a) Convection.

a) Convection – There is transport of water between the water in regolith and surface water. This interaction is of importance for the transport of radionuclides from the repository to the surface and needs to be considered in a safety assessment for a repository at Forsmark.

3:5 Water in regolith affects **gas and local atmosphere** by the process a) Radioactive decay, and b) Phase transitions.

a) Radioactive decay – Decay of some radionuclides in water forms elements in the gas phase, e.g. Ra decaying to Rn, and thereafter these can readily be transported via gas. Radon is an example of a gas that can penetrate buildings and in some cases accumulate in areas with deficient ventilation. This interaction needs to be considered in a safety assessment for a repository at Forsmark.

b) Phase transitions – Water in the regolith may become gaseous and thus a part of the component gas and local atmosphere. This interaction is a transport pathway for water and should be considered for hydrological mass balances. Only a few radionuclides are released into the gaseous phase without biological interactions, but a few radionuclides dissolved in water, e.g. I-129 and C-14 as carbon dioxide, may transfer to gas phase and for these radionuclides the process may be important. Thus, this interaction needs to be considered in a safety assessment for a repository at Forsmark.

3:6 Water in regolith affects **primary producers** by the processes a) Element supply, b) Exposure, c) Habitat supply, d) Stimulation/inhibition, and e) Water supply.

a) Element supply – Primary producers take up nutrients from water in regolith and surface water. Nutrients may limit the production of primary producers and thus this interaction needs to be considered in a safety assessment for a repository at Forsmark.

b) Exposure – Exposure can either be external due to sources outside the body or internal due to sources inside the body. Concentration, location and type of radionuclides in surface waters, groundwater, regolith, and in the atmosphere, i.e. in all parts of the biosphere system, affect the external exposure of, and the radiologic and toxic effects on, biota. This interaction needs to be considered in a safety assessment for a repository at Forsmark.

c) Habitat supply – Parts of primary producers (e.g. roots) may be situated in water in the regolith. However, in general, primary producers are more dependent on nutrient concentrations (element supply), light conditions and regolith characteristics (e.g. grain size, porosity) than on the amount of water in the regolith. Therefore, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

d) Stimulation/inhibition – The temperature and composition of water in regolith may influence the pattern of settlement as different species thrive at different temperatures and are affected by aspects of chemical composition such as different pH values. Moreover, the temperature will affect the metabolism and secondary production of biota and that may be important for distribution of radionuclides in the biotic community and exposure to man. Therefore, this interaction needs to be considered in a safety assessment for a repository at Forsmark.

e) Water supply – The amount of water in the regolith can affect biota on land. In aquatic and terrestrial (mire) ecosystems, the regolith is always saturated with water and therefore this interaction does not need to be considered. However, for agricultural systems, the water in regolith may determine the need for irrigation which is a potential pathway for radionuclide transport. Thus, this interaction needs to be considered in a safety assessment for a repository at Forsmark.

3:7 Water in regolith affects **decomposers** by the processes a) Element supply, b) Exposure, c) Habitat supply, d) Stimulation/inhibition, and e) Water supply.

a) Element supply – Decomposers (e.g. bacteria) take up nutrients from water in regolith and surface water. Nutrients may limit their growth and thus this interaction needs to be considered in a safety assessment for a repository at Forsmark.

b) Exposure – Exposure can either be external due to sources outside the body or internal due to sources inside the body. Concentration, location and type of radionuclides in surface waters, groundwater, regolith, and in the atmosphere, i.e. in all parts of the biosphere system, affect the external exposure of, and the radiologic and toxic effects on, biota. This interaction needs to be considered in a safety assessment for a repository at Forsmark.

c) Habitat supply – Decomposers may live in the water in the regolith. However, in general, they are more dependent on nutrient concentrations (element supply), light conditions and regolith characteristics (e.g. grain size, porosity) than on the amount of water in the regolith. Therefore, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

d) Stimulation/inhibition – The temperature and composition of water in the regolith may influence the pattern of settlement, as different species thrive at different temperatures and are affected by aspects of chemical composition, such as different pH values. Moreover, the temperature will affect the metabolism and secondary production of biota and that may be important for distribution of radionuclides in the biotic community and exposure of man. Therefore, this interaction needs to be considered in a safety assessment for a repository at Forsmark.

e) Water supply – The amount of water in the regolith can affect biota on land. It is mainly primary producers that are limited by access to water and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

3:8 Water in regolith affects **filter feeders** by the processes a) Exposure, b) Stimulation/inhibition, and c) Water supply.

a) Exposure – Exposure can either be external due to sources outside the body or internal due to sources inside the body. Concentration, location and type of radionuclides in surface waters, groundwater, regolith, and in the atmosphere, i.e. in all parts of the biosphere system, affect the external exposure and the radiologic and toxic effects on biota. This interaction needs to be considered in a safety assessment for a repository at Forsmark.

b) Stimulation/inhibition – Temperature and composition of water in regolith may influence the pattern of settlement as different species thrive at different temperatures and are affected by aspects of chemical composition, such as different pH values. Moreover, the temperature will affect the metabolism and secondary production of biota and that may be important for distribution of radionuclides in the biotic community and exposure of man. Therefore, this interaction needs to be considered in a safety assessment for a repository at Forsmark.

c) Water supply – The amount of water in the regolith can affect biota on land. It is mainly primary producers that are limited by the access to water and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

3:9 Water in regolith affects **herbivores** by the processes a) Exposure, b) Stimulation/inhibition, and c) Water supply.

a) Exposure – Exposure can either be external due to sources outside the body or internal due to sources inside the body. Concentration, location and type of radionuclides in surface waters, groundwater, regolith, and in the atmosphere, i.e. in all parts of the biosphere system, affect the external exposure and the radiologic and toxic effects on biota. This interaction needs to be considered in a safety assessment for a repository at Forsmark.

b) Stimulation/inhibition – The temperature and composition of water in the regolith may influence the pattern of settlement as different species thrive at different temperatures and are affected by aspects of chemical composition, such as different pH values. Moreover, the temperature will affect the metabolism and secondary production of biota and that may be important for distribution of radionuclides in the biotic community and exposure of man. Therefore, this interaction needs to be considered in a safety assessment for a repository at Forsmark.

c) Water supply – The amount of water in the regolith can affect biota on land. It is mainly primary producers that are limited by the access to water and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

3:10 Water in regolith affects **carnivores** by the processes a) Exposure, b) Stimulation/inhibition, and c) Water supply.

a) Exposure – Exposure can either be external due to sources outside the body or internal due to sources inside the body. Concentration, location and type of radionuclides in surface waters, groundwater, regolith, and in the atmosphere, i.e. in all parts of the biosphere system, affect the external exposure and the radiologic and toxic effects on biota. This interaction needs to be considered in a safety assessment for a repository at Forsmark.

b) Stimulation/inhibition – The temperature, composition and amount of water in the regolith may influence the pattern of settlement as different species thrive at different temperatures and are affected by aspects of chemical composition such as different pH-values. Moreover, the temperature will affect the metabolism and secondary production of biota and that may be important for distribution of radionuclides in the biotic community and exposure of man. Therefore this interaction needs to be considered in a safety assessment for a repository at Forsmark.

c) Water supply – The amount of water in the regolith can affect biota on land. It is mainly primary producers that are limited by the access to water and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

3:11 Water in regolith affects **humans** by the process a) Exposure, b) Stimulation/inhibition, and c) Water supply.

a) Exposure – Exposure can either be external due to sources outside the body or internal due to sources inside the body. Concentration, location and type of radionuclides in surface waters, groundwater, regolith, and in the atmosphere, i.e. in all parts of the biosphere system, affect the external exposure of, and the radiologic and toxic effects on, humans. This interaction needs to be considered in a safety assessment for a repository at Forsmark.

b) Stimulation/inhibition – The water composition (e.g. salinity and toxicants) may affect humans and concentrations of toxic elements and salinity determine human utilisation of water resources. Thus, this interaction needs to be considered in a safety assessment for a repository at Forsmark.

c) Water supply – The amount of water in regolith affects the amount of water that can be extracted by humans. This may affect the location of wells and the number of people living in an area and thus the transport of radionuclides to humans. Therefore, this interaction needs to be considered in a safety assessment for a repository at Forsmark.

3:12 Water in regolith affects **external conditions** by the process a) Export.

a) Export – Water in the regolith is exported to external water volumes. Since amounts of exported water will most probably be small compared with the volumetric flows in external objects (downstream lakes or marine basins), the effects of exported water on the receiving ecosystem should be small. However, although exports of radionuclides via groundwater are also assumed to have small effect on the surrounding ecosystems due to dilution (downstream in a catchment), there are theoretical situations of interest with the receiving system being very small or receiving inputs from several upstream objects. Thus, this interaction needs to be considered in a safety assessment for a repository at Forsmark, to provide assurance that concentrations in receiving ecosystems are lower than in the exporting system and that radiological impacts are also lower.

4:1 Surface water affects **geosphere** by the processes a) Change of pressure, b) Convection, c) Loading, and d) Weathering.

a) Change of pressure – The pressure of the water column may affect the pore water pressure in the rock. However, surface-water-level fluctuations are modest in Forsmark and there should be small changes in pressure over time due to surface water pressure. Therefore, the effect of water column changes does not need to be considered in a safety assessment for a repository at Forsmark. During glaciations, changes in the thickness of an ice sheet will affect the mechanical stress in the rock but this aspect is treated in loading below.

b) Convection – The surface-water hydrology influences the recharge and discharge of groundwater and thereby the hydrology and composition of water in the geosphere. This interaction may be important for the transport of radionuclides and needs to be considered in a safety assessment for a repository at Forsmark. Heat transport from the biosphere to the geosphere may affect the temperature in the geosphere. The flux of heat and the resulting temperature distribution is important, since permafrost conditions may lead to freezing temperatures in the geosphere. However, although the effects in terms of increased/decreased releases of radionuclides should be considered, the temperature effect on the geosphere does not need to be considered in the biosphere part of a safety assessment for a repository at Forsmark.

c) Loading – Changes in thickness of an ice sheet during periods of glaciation and deglaciation will affect the mechanical stress in the rock. Effects on the geosphere are not a part of the biosphere modelling and thus does not need to be considered in the biosphere part of a safety assessment for a repository at Forsmark.

d) Weathering – Surface water flow influences the weathering of rock by e.g. ice scoring in near-shore areas. Weathering will not add radionuclides originating from the repository and therefore this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

4:2 Surface water affects **regolith** by the processes a) Deposition, b) Relocation, c) Resuspension, d) Saturation, e) Sorption/desorption and f) Weathering.

a) Deposition – Sedimentation of particles and elements (i.e. the feature Water composition) affect the composition of the regolith and can be important for the transport of radionuclides. In addition, the concentration of particles in the water affects the sedimentation rate and amount of sedimentated material, i.e. the deposition. Thus, this interaction needs to be considered in a safety assessment for a repository at Forsmark.

b) Relocation – Surface water may affect the regolith by erosion i.e. relocating regolith from one point to another. This interaction is especially significant in the Forsmark area due to erosion during land-rise. When marine basins become shallower, there is often large degree of erosion in high-energy environments (which are dependent on bathymetry, currents and wind and often occur at intermediate depths). The relocated regolith is transported from transport bottoms to deeper accumulation bottoms. This interaction is important for the distribution of radionuclides in the ecosystem and needs to be considered in a safety assessment for a repository at Forsmark.

c) Resuspension – The magnitude and direction of water flow determines the amount of the regolith that takes part of resuspension. This interaction is important for the distribution of radionuclides between regolith and surface water and needs to be considered in a safety assessment for a repository at Forsmark.

d) Saturation – The magnitude and direction of the water flow influences the water content in the regolith. In aquatic ecosystems and in the terrestrial mire ecosystem, the regolith is always saturated with water and this interaction does not need to be considered. However, in agricultural ecosystems, saturation may determine the need for irrigation which may be an important pathway for radionuclide transport. Thus, this interaction needs to be considered in a safety assessment for a repository at Forsmark.

e) Sorption/desorption – The composition and grain size (available surfaces for sorption) of the regolith will affect the extent of sorption of radionuclides and thereby the distribution of radionuclides between regolith and water. The degree of sorption of radioactive elements is important for transport and accumulation of radionuclides and thus needs to be considered in a safety assessment for a repository at Forsmark.

f) Weathering – The composition of water (i.e. the feature Water composition) influences the weathering of the regolith. For example the pH of water affects the amount of weathering. However, other factors are assumed to have larger effect on the regolith and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

4:3 Surface water affects **water in regolith** by the process a) Convection.

a) Convection – There is a transport of water between surface water and water in regolith that will affect the hydraulic situation in the regolith. This interaction is important for transport of radionuclides and needs to be considered in a safety assessment for a repository at Forsmark.

4:4 Surface water is a diagonal element defined as water collecting on the ground or in streams, rivers, lakes wetlands, or oceans, as opposed to groundwater or atmospheric water, and is further described in Chapter 4. Surface water is internally affected by the features Geometry, Material composition, Stage of succession, Temperature, Water composition and Radionuclide inventory. Surface water affects surface water by the following processes: a) Change of pressure, b) Convection, c) Heat storage, d) Light-related processes, e) Phase transitions, f) Physical properties, g) Radioactive decay, h) Radiolysis, i) Reactions, and j) Sorption/desorption.

a) Change of pressure – At large depths, normally only occurring in the sea, adiabatic temperature increase may occur. Water with high density sinks by gravitational forces and water becomes compressed when the pressure increases. The compression leads to release of heat and thus a temperature increase, the so called adiabatic temperature increase. However, very large water depths are needed to significantly increase the temperature, and the adiabatic temperature increase in sea water varies between 0.02 and 0.2°C per 1,000 m. Thus, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

b) Convection – Fluxes of water (i.e. convection) are important since they may be an important transport route for radionuclides in the biosphere. Convection is altered by features associated with surface waters in the following ways:
   - Changes in surface water temperature influence water densities and thus surface water movements and water renewal times. Temperature variations are important for mixing of water columns and thus need to be considered in a safety assessment for a repository at Forsmark. Temperature also affects diffusion, but the mixing process due to water movement is assumed to be much larger than the molecular diffusion and diffusion does not need to be considered for surface waters.
   - Water composition affects viscosity and density which in turn affect the transport of water. Since water transport is important for the transport of radionuclides, this interaction needs to be considered in a safety assessment for a repository at Forsmark.
   - The geometry of surface water bodies affect the flow pattern of the water and mixing of the water column. e.g. deep water columns are often stratified during summer and winter in Sweden, whereas shallow water bodies are often completely mixed.
   - The radionuclide inventory is affected by convection, since water fluxes affect the concentrations of radionuclides in surface waters and this has to be considered in a safety assessment for a repository at Forsmark. Stratification, i.e. the opposite of mixing may lead to an uneven distribution of radionuclides in the water column. However, it is assumed that the effects of stratification are reversed during one year and that homogenous mixing is a good approximation of the long-term distribution in the water column. Thus, the lack of mixing (i.e. convection) does not have to be considered in a safety assessment for a repository at Forsmark.

c) Heat storage – The amount and thermal properties of surface waters affect the heat storage capacity and thus the temperature in the surface waters. The heat storage in surface water is important for the circulation of water and heat storage influences the formation of taliks during permafrost conditions. Thus, this interaction needs to be considered in a safety assessment for a repository at Forsmark.

d) Light-related processes – Wave-formation on the surface waters, and surface water area, water volume, and amount of particles in surface water, affect light reflection and the amount of radiation that is adsorbed and thereby the temperature in the surface waters. This is an important interaction that needs to be considered in a safety assessment for a repository at Forsmark.

e) Phase transitions – The water composition in the different parts of the biosphere system may affect the dissolution/precipitation of radionuclides and thus the distribution of radionuclides between the water phase and bulk solids or particulate matter. Radionuclides are assumed to be dissolved in water in order to be transported to the biosphere and thus dissolution/precipitation does not need to be considered in a safety assessment for a repository at Forsmark. Temperature affects the state of water (solid, liquid or gaseous). Freezing and evaporation of surface waters as a result of changes in temperature will affect water movement and amounts of water and ice. Ice coverage is important for transport of radionuclides, e.g. it prevents transport of radionuclides between surface waters and the atmosphere. Thus, phase transitions need to be considered in a safety assessment for a repository at Forsmark.

f) Physical properties change – The density and viscosity of water is the driving force for the turnover of water. Thus, density and salinity are important in calculations of water turnover and need to be considered in a safety assessment for a repository at Forsmark. At very large depths, generally only occurring in the sea, water is compressed and this may cause density effects. During an interglacial, the aquatic ecosystems in Forsmark will at a maximum have relatively shallow depths (< 200 m). Hence, density changes due to differences in depth do not need to be considered.

g) Radioactive decay – Radionuclides in the different biosphere components undergo radioactive decay where they transform into other radionuclides or form stable isotopes. Decay of radionuclides is important to consider in estimating the amounts of different radionuclides in the biosphere and this process needs to be considered in a safety assessment for a repository at Forsmark. The build-up of stable isotopes due to radioactive decay may affect the composition of the water. However, the amounts of radionuclides originating from a repository are too small to have any significant effect on the water composition and this aspect of decay does not need to be considered.

h) Radiolysis – Radiation from decaying radionuclides may cause radiolytic decomposition of the water and thereby affect the water composition in the different components of the biosphere system. However, concentrations of radionuclides from a repository will be too small for radiolysis to have any significant effect on water composition and thus this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

i) Reactions – Reactions within surface waters may affect the composition and temperature of the water. Reactions in water may change the form of different elements. For example, C-14 can occur in many forms of which some are easily utilised by plants (carbon dioxide) whereas others are not (methane). By reactions, methane can transform to CO_2 which then has a large effect on the bioavailability of any C-14 initially present as methane. Reactions are dependent on water composition (e.g.in the case of methane and carbon dioxide the availability of oxygen) and on temperature. The reactions can require heat or release heat and thereby influence the temperature of surface waters. Other factors (such as insolation) are assumed to have greater influence on temperature. But the effect of reactions in water and consequent changes in water composition need to be considered in a safety assessment for a repository at Forsmark.

j) Sorption/desorption – The water composition and amount of particles in the water affects the distribution of radionuclides between particles and water. This is important for the transport of radionuclides and needs to be considered in a safety assessment for a repository at Forsmark.

4:5 Surface water affects **gas and local atmosphere** by the processes a) Covering, b) Phase transitions, c) Relocation, and d) Resuspension.

a) Covering – At cold temperatures surface water freeze and the ice sheet on aquatic ecosystems can prevent exchange of gases and particles between the water and the atmosphere. This can be of importance for certain radionuclides and need to be considered in a safety assessment for a repository at Forsmark.

b) Phase transitions – Surface water may affect the atmosphere by transformation of water in surface waters to the gas phase by evaporation and sublimation. Evaporation is an important process for water balance, but the effects on the local atmosphere are assumed to be negligible compared with air exchange between the local and global atmosphere. However, evaporation may be important for the water balance for the surface system, and in addition, phase transitions may be important for the transport of some radionuclides in surface water to the atmosphere, e.g. C-14. Thus, this interaction needs to be considered in a safety assessment for a repository at Forsmark.

c) Relocation – The release of water droplets as sea spray or snow from snowdrifts influences the composition of gas. Both small and large particles may be released and thus, both relocation and resuspension occur (see below). In lakes, this interaction is assumed to have minor effect on the atmosphere. In seas, sea spray may influence the atmosphere and thereby also terrestrial ecosystems located close to the coast. However, as radionuclides are heavily diluted in the seas, sea spray will contain very small amounts of radionuclides and this interaction is not considered important for transport of radionuclides. Consequently, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

d) Resuspension – The release of water droplets as sea spray or snow from snowdrifts influences the composition of gas. Both small and large particles may be released and thus, both relocation and resuspension occur (see above). In lakes, this interaction is assumed to have minor effect on the atmosphere. In seas, sea spray may influence the atmosphere and thereby also terrestrial ecosystems located close to the coast. However, as radionuclides are heavily diluted in the seas, sea spray will contain very small amounts of radionuclides and this interaction is not considered important for transport of radionuclides. Consequently, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

4:6 Surface waters affect **primary producers** by the processes a) Element supply, b) Exposure, c) Habitat supply, d) Light-related processes e) Relocation, f) Stimulation/inhibition, and g) Water supply.

a) Element supply – Primary producers in ecosystems take up nutrients from water in regolith and surface waters. Nutrients may limit the production of primary producers and thus this interaction needs to be considered in a safety assessment for a repository at Forsmark.

b) Exposure – Exposure can either be external due to sources outside the body or internal due to sources inside the body. Concentration, location and type of radionuclides in surface waters, groundwater, regolith, and in the atmosphere, i.e. in all parts of the biosphere system, affect the external exposure of, and the radiologic and toxic effects on, biota. This interaction needs to be considered in a safety assessment for a repository at Forsmark.

c) Habitat supply – Surface water is important for the settlement of organisms and the amount of surface water affects the amount of aquatic primary producers. Therefore, this interaction needs to be considered in a safety assessment for a repository at Forsmark.

d) Light-related processes – Water composition influences the light attenuation which in turn influences primary production in ecosystems. This determines the distribution of primary producers and needs to be considered in a safety assessment for a repository at Forsmark.

e) Relocation – Relocation of organisms from one part of a aquatic basin to another has no major effect on the transport and accumulation of radionuclides at the ecosystem scale. Thus, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

f) Stimulation/inhibition – The water composition (e.g. salinity and pH-value) and temperature of surface waters will affect the production of primary producers and thereby amount of primary producers. Moreover, the temperature will affect the metabolism and secondary production of biota and that may be important for the distribution of radionuclides in the biotic community and exposure of man. Biomass production is important for accumulation and transport of radionuclides and this interaction needs to be considered in a safety assessment for a repository at Forsmark.

g) Water supply – In aquatic ecosystems and in mires the organisms are, by definition, always surrounded by water, and therefore uptake of water is never limiting the uptake of radionuclides. Organisms in other terrestrial ecosystems than mires may be limited by water supply. In those cases, irrigation may need to be considered, i.e. this interaction needs to be considered for terrestrial ecosystems in a safety assessment for a repository at Forsmark.

4:7 Surface waters affect **decomposers** by the processes a) Element supply, b) Exposure, c) Food supply, d) Habitat supply, e) Relocation, f) Stimulation/inhibition and g) Water supply.

a) Element supply – Aquatic decomposers use oxygen in surface water. Oxygen concentrations may be low in winter in shallow lakes and thereby limit the occurrence of macro-decomposers. Moreover, bacterioplankton in surface water can use dissolved organic carbon and nutrients as food. This may affect accumulation and transport of radionuclides and needs to be considered in a safety assessment for a repository at Forsmark.

b) Exposure – Exposure can either be external due to sources outside the body or internal due to sources inside the body. Concentration, location and type of radionuclides in surface waters, groundwater, regolith, and in the atmosphere, i.e. in all parts of the biosphere system, affect the external exposure of, and the radiologic and toxic effects on, biota. This interaction needs to be considered in a safety assessment for a repository at Forsmark.

c) Food supply – Some bacteria feed on particulate matter in water as well as on dissolved organic carbon. Carbon may be limiting for the production of bacteria. However, generally bacteria are more dependent on organic matter in sediments, dissolved organic carbon (element supply) and temperature, and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

d) Habitat supply – Surface water is important for the settlement of organisms and the amount of surface water affects the amount of aquatic biota. Therefore, this interaction needs to be considered in a safety assessment for a repository at Forsmark.

e) Relocation – Relocation of sessile organisms from one part of aquatic basins to another has no major effect on the transport and accumulation of radionuclides at the ecosystem scale. Thus, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

f) Stimulation/inhibition – The water composition (e.g. salinity and pH-value) and temperature of surface waters will affect the occurrence of decomposers. Moreover, the temperature will affect the metabolism and secondary production of biota and that may be important for distribution of radionuclides in the biotic community and exposure of man. Biomass and production is important for accumulation and transport of radionuclides and this interaction needs to be considered in a safety assessment for a repository at Forsmark.

g) Water supply – In aquatic ecosystems and in mires the organisms are, by definition, always surrounded by water, and therefore uptake of water never limits the uptake of radionuclides. Organisms in terrestrial ecosystems other than mires may be limited by water supply. However, decomposers are more dependent on the amount of available substrate to decompose and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

4:8 Surface water affects **filter feeders** by the processes a) Element supply, b) Exposure, c) Food supply, d) Habitat supply, e) Relocation, f) Stimulation/inhibition and f) Water supply.

a) Element supply – Filter feeders use elements e.g. oxygen in surface water. Although oxygen concentrations can be low in winter especially in lakes, the supply is considered to be enough to support a permanent population of filter feeders and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

b) Exposure – Exposure can either be external due to sources outside the body or internal due to sources inside the body. Concentration, location and type of radionuclides in surface waters, groundwater, regolith, and in the atmosphere, i.e. in all parts of the biosphere system, affect the external exposure of, and the radiologic and toxic effects on, biota. This interaction needs to be considered in a safety assessment for a repository at Forsmark.

c) Food supply – Filter feeders feed on, among other things, resuspended particles. This may be an important transport pathway for radionuclides and needs to be considered in a safety assessment for a repository at Forsmark.

d) Habitat supply – Surface water is important for the settlement of organisms and the amount of surface water affects the amount of aquatic biota. Therefore, this interaction needs to be considered in a safety assessment for a repository at Forsmark.

e) Relocation – Relocation of sessile organisms from one part of aquatic basins to another has no major effect on the transport and accumulation of radionuclides at the ecosystem scale. Thus, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

f) Stimulation/inhibition – The water composition (e.g. salinity and pH value) and temperature of surface waters will affect the occurrence of filter feeders. Moreover, the temperature will affect the metabolism and secondary production of biota and that may be important for distribution of radionuclides in the biotic community and exposure of man. Biomassproduction is important for accumulation and transport of radionuclides and this interaction needs to be considered in a safety assessment for a repository at Forsmark.

g) Water supply – Filter feeders are only present in aquatic ecosystems where they, by definition, are always surrounded by water. Therefore, uptake of water never limits the uptake of radionuclides and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

4:9 Surface waters affect **herbivores** by the processes a) Element supply, b) Exposure, c) Habitat supply, d) Relocation, e) Stimulation/inhibition, and f) Water supply.

a) Element supply – Aquatic and terrestrial herbivores may use essential elements in surface water, e.g. aquatic herbivores utilise dissolved oxygen in the water. In shallow lakes, oxygen concentrations may be low in winter and thereby limit the occurrence of some herbivores, e.g. crayfish and fish. This may affect accumulation and transport of radionuclides and needs to be considered in a safety assessment for a repository at Forsmark.

b) Exposure – Exposure can either be external due to sources outside the body or internal due to sources inside the body. Concentration, location and type of radionuclides in surface waters, groundwater, regolith, and in the atmosphere, i.e. in all parts of the biosphere system, affect the external exposure of, and the radiologic and toxic effects on, biota. This interaction needs to be considered in a safety assessment for a repository at Forsmark.

c) Habitat supply – Surface water is important for the settlement of organisms and the amount of surface water affects the amount of aquatic biota. Therefore, this interaction needs to be considered in a safety assessment for a repository at Forsmark.

d) Relocation – Relocation of sessile organisms from one part of aquatic basins to another has no major effect on the transport and accumulation of radionuclides at the ecosystem scale. Thus, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

e) Stimulation/inhibition – The water composition (e.g. salinity and pH-value) and temperature of surface waters will affect the occurrence of herbivores. Moreover, the temperature will affect the metabolism and secondary production of biota and that may be important for distribution of radionuclides in the biotic community and exposure of man. Biomass production is important for accumulation and transport of radionuclides and this interaction needs to be considered in a safety assessment for a repository at Forsmark.

f) Water supply – In aquatic ecosystems and in mires the organisms are, by definition, always surrounded by water, and, therefore, uptake of water never limits the uptake of radionuclides. Organisms in terrestrial ecosystems other than mires may be limited by water supply. However, herbivores are more dependent on the amount of primary producers and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

4:10 Surface waters affect **carnivores** by the processes a) Element supply, b) Exposure, c) Habitat supply, d) Relocation, e) Stimulation/inhibition, and f) Water supply.

a) Element supply – Aquatic carnivores use oxygen and terrestrial carnivores may use essential elements in surface water. In shallow lakes, oxygen concentrations may be low in winter and thereby limit the occurrence of some carnivores, e.g. fish. This may affect accumulation and transport of radionuclides and needs to be considered in a safety assessment for a repository at Forsmark.

b) Exposure – Exposure can either be external due to sources outside the body or internal due to sources inside the body. Concentration, location and type of radionuclides in surface waters, groundwater, regolith, and in the atmosphere, i.e. in all parts of the biosphere system, affect the external exposure of, and the radiologic and toxic effects on, biota. This interaction needs to be considered in a safety assessment for a repository at Forsmark.

c) Habitat supply – Surface water is important for the settlement of organisms and the amount of surface water affects the amount of aquatic biota. Therefore, this interaction needs to be considered in a safety assessment for a repository at Forsmark.

d) Relocation – Relocation of sessile organisms from one part of aquatic basins to another has no major effect on the transport and accumulation of radionuclides at the ecosystem scale. Thus, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

e) Stimulation/inhibition – The water composition (e.g. salinity and pH value) and temperature of surface waters will affect carnivores. Moreover, the temperature will affect the metabolism and secondary production of biota and that may be important for distribution of radionuclides in the biotic community and exposure of man. Biomass production is important for accumulation and transport of radionuclides, and this interaction needs to be considered in a safety assessment for a repository at Forsmark.

f) Water supply – In aquatic ecosystems and in mires the organisms are, by definition, always surrounded by water, and, therefore, uptake of water never limits the uptake of radionuclides. Organisms in terrestrial ecosystems other than mires may be limited by water supply. However, carnivores are more dependent on the amount of available prey and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

4:11 Surface waters affect **humans** by the by the processes a) Exposure, b) Habitat supply, c) Stimulation/inhibition, and d) Water supply.

a) Exposure – Exposure can either be external due to sources outside the body or internal due to sources inside the body. Concentration, location and type of radionuclides in surface waters, groundwater, regolith, and in the atmosphere, i.e. in all parts of the biosphere system, affect the external exposure of, and the radiologic and toxic effects on, humans. This interaction needs to be considered in a safety assessment for a repository at Forsmark.

b) Habitat supply – Human settlement is mainly determined by the area and type of the ecosystems, since this determines the amount of available food. The size and location of surface waters thereby affects the settlement of humans in the area and this interaction needs to be considered in a safety assessment for a repository at Forsmark.

c) Stimulation/inhibition – The water composition (e.g. salinity and toxicants) may affect humans and concentrations of toxic elements and salinity determine human utilisation of water resources. Thus, this interaction needs to be considered in a safety assessment for a repository at Forsmark.

d) Water supply – Water is extracted for drinking and other purposes by humans. Water supply may limit human utilisation of water bodies and this interaction needs to be considered in a safety assessment for a repository at Forsmark.

4:12 Surface waters affect **external conditions** by the processes a) Export, and b) Import.

a) Export – Export of surface water includes the water flow from an upstream to a downstream water body and water flooding from streams and lakes into terrestrial areas during periods with heavy water flows. Although, from an ecological viewpoint, flooding may have large effect, the effect of transported radionuclides from an upstream to downstream object should be minor due to dilution in the receiving object. However, if the receiving object is small, and receives input from several upstream sources, the effects could be larger in a secondary object than in a primary one, and this interaction needs to be considered in a safety assessment for a repository at Forsmark.

b) Import – If water and elements are imported to a modelled area from an outside area (e.g. import of water to a future Forsmark lake or sea basin from the Baltic Sea) there may be an affect both in the model area and in the outside area from which the import occurs. Although the effect of an import may be large for the modelled area, the effect on the outside area should in most cases be minor (e.g. Baltic Sea). Therefore, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

5:1 Gas and local atmosphere affect **geosphere** by the process a) Convection.

a) Convection – Air intrusion can take place via human activities and can also be a consequence of land-rise and climatic changes leading to unsaturated conditions. However, air flow from the atmosphere reaching the repository (i.e. comparable to intrusion by organisms) is an indirect interaction since it occurs in the geosphere and is therefore not considered in the biosphere assessment.

5:2 Gas and local atmosphere affect **the regolith** by the processes a) Deposition, b) Reactions, c) Relocation, d) Resuspension.

a) Deposition – The amount of particles in the atmosphere and the wind velocity will affect the amount of deposited particles and thereby the amount, geometry and composition of the regolith. The transport of fine material is limited in the Forsmark area and thus also the deposition. Therefore, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

b) Reactions – Elements in the gas phase in regolith may react with the regolith. Other factors (e.g. elements dissolved in water) are assumed to have greater impacts on the regolith. Therefore, this interaction is of minor importance for transport and accumulation of radionuclides and does not need to be considered in a safety assessment for a repository at Forsmark.

c) Relocation – In terrestrial ecosystems, the strength of the wind influence erosion, and thereby the geometry and amount of regolith at a site. In the Forsmark area with wave washed till there is a small amount of fine particles in the deposits and the erosion is small and likewise so is the effect on the regolith. Thus, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

d) Resuspension – In terrestrial ecosystems, the strength of the wind determines the amount of particles that will be resuspended in the air. In the Forsmark area with wave washed till there is a small amount of fine particles in deposits and the erosion is small. Although the amount of particles resuspended in the air might be important for the atmosphere, the effect on the regolith will be small. Thus, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

5:3 Gas and local atmosphere affect **water in regolith** by the processes a) Convection, and b) Phase transitions.

a) Convection – The atmospheric pressure and the pressure of existing gas will affect the location of the groundwater table and thus also the water content and the water movement in the regolith. This interaction can lead to upward transport of radionuclides in the soil and needs to be considered in a safety assessment for a repository at Forsmark.

b) Phase transitions – Water in the gas phase of the regolith may condense and become liquid thereby a part of water in regolith. This interaction is of minor importance compared with other processes affecting the amount of water in the regolith and does not need to be considered in a safety assessment for a repository at Forsmark.

5:4 Gas and local atmosphere affect **surface waters** by the processes a) Convection, b) Deposition, c) Phase transitions, and d) Wind stress.

a) Convection – The atmospheric pressure will affect surface water levels and thus also the distribution of surface waters and water movements such as water turnover. This is important for the distribution and transport of radionuclides and thus need to be considered in a safety assessment for a repository at Forsmark.

b) Deposition – Deposition includes sedimentation, rainfall, and snowfall. The magnitude of the precipitation will influence the amounts of surface waters and the amounts of ice/snow on surfaces. This is important for the distribution and transport of radionuclides and thus need to be considered in a safety assessment for a repository at Forsmark. Precipitation will also influence the water composition.

c) Phase transitions – The atmosphere may affect the surface water by the transformation of water in surface waters to the gas phase by dissolution, degassing, evaporation and sublimation. Phase transitions are important for amounts of water, water movement and water turnover. This is important for the distribution and transport of radionuclides and thus need to be considered in a safety assessment for a repository at Forsmark.

d) Wind stress – The strength and direction of the wind will affect the movement of surface waters, e.g. wave formation and mixing of the water column. This is important for the distribution and transport of radionuclides and needs to be considered in a safety assessment for a repository at Forsmark. Minor amounts of surface water may also be blown away (i.e. sea spray) by the wind and cause concentration differences in the water composition. The magnitude of this process is assumed to be very small.

5:5 Gas and local atmosphere is a diagonal element defined as the layer of gases above the ecosystem that participates in gas exchange with the water, as further described in Chapter 4. The gas composition and the gas flow are included in this element. This element also includes atmospheric flow and wind. Features affect gas and local atmosphere by the following processes a) Change of pressure, b) Convection, c) Heat Storage, d) Light-related processes, e) Phase transitions, f) Radioactive decay, g) Reactions, and h) Sorption/desorption.

a) Change of pressure – Temperature of the atmosphere is an important mechanism influencing the turnover of the atmosphere and changes in temperature contribute to pressure changes that affect air movements. However, local atmosphere changes are assumed to have small effect compared with large-scale regional temperature changes. Changes in air pressure may also affect the temperature of the atmosphere, so called adiabatic temperature changes. This is assumed to have a minor effect on temperature in comparison with solar radiation. Consequently, this process does not need to be considered in a safety assessment for a repository at Forsmark.

b) Convection – Convection covers the flux of radionuclides, elements, and temperature:
   - The distribution, magnitude and direction of gas (including air) flow in the different compartments of the biosphere affects the concentrations of radionuclides in the gas phase in the compartments. This may be important for certain radionuclides, e.g. I-129 and C-14 and for these this interaction needs to be considered in a safety assessment for a repository at Forsmark.
   - Convection of heat (temperature) influences diffusion but also, more importantly, the stratification of the atmosphere and thereby the composition of the atmosphere and fluxes of elements. However, external influences are assumed to be of greater importance than this local effect. Heat transport within the atmosphere is rapid, but the temperature changes in ecosystems are dampened due to the heat storage of water and regolith. Overall, the convection of heat within the local atmosphere does not need to be considered in a safety assessment for a repository at Forsmark.

c) Heat storage – Heat storage of the atmosphere may affect the temperature of the atmosphere and ecosystems beneath. However, the heat storage in the local atmosphere is limited compared with the storage in soil and water and thus this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

d) Light-related processes – The composition of the atmosphere affects the absorption/scattering/reflection of radiation and thus the temperature of the atmosphere and ecosystems beneath. Even though there are minor changes in air composition over the year, this is not assumed to result in large changes in temperature due to altered absorbing/scattering/reflection, but instead temperature of the atmosphere is more dependent on insolation (interaction 12:5). Thus this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

e) Phase transitions – Phase transitions are the changes between solid, liquid and gas. Temperature effects on gas are an important driving mechanism for phase transitions in the atmosphere. Phase transitions can be exo- or endothermic and thereby affect the temperature. Other factors (e.g. heat storage of surface waters and regolith) will have greater impact on temperature in the ecosystems. Moreover, external influences are assumed to have a larger effect on phase transitions than the local effect and therefore, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

f) Radioactive decay – Radionuclides in the different biosphere components undergo radioactive decay where they transform into other radionuclides or form stable isotopes. Decay of radionuclides is important to consider in estimating the amounts of different radionuclides in the biosphere and this process needs to be considered in a safety assessment for a repository at Forsmark.

g) Reactions – Reactions may influence the composition of the atmosphere and also the temperature. Reactions in the local atmosphere are not assumed to significantly affect the composition of the atmosphere and other factors (e.g. heat storage of surface waters and solar insolation) will have greater impact on temperature. Thus, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

h) Sorption/desorption – The atmosphere could potentially influence the distribution of radionuclides in the atmosphere by sorption of radionuclides in the gas phase on particles, pollen and water drops in the atmosphere. For most radionuclides, this interaction is insignificant, but for some radionuclides, e.g. I-129 in water droplets, this could have an influence. Thus, depending on radionuclides involved, this interaction may need to be considered in a safety assessment for a repository at Forsmark.

5:6 Gas and local atmosphere affect **primary producers** by the processes a) Element supply, b) Exposure, c) Relocation, and d) Stimulation/inhibition.

a) Element supply – Primary producers utilise carbon dioxide and nutrients for photosynthesis and growth. In terrestrial ecosystems, carbon dioxide is taken up from the atmosphere. The uptake of carbon dioxide by terrestrial primary producers can be an important pathway for some radionuclides (e.g. C-14) into biota and this interaction needs to be considered in a safety assessment for a repository at Forsmark.

b) Exposure – Exposure can either be external due to sources outside the body or internal due to sources inside the body. Concentration, location and type of radionuclides in surface waters, groundwater, regolith, and in the atmosphere, i.e. in all parts of the biosphere system, affect the external exposure of, and the radiologic and toxic effects on, biota. This interaction needs to be considered in a safety assessment for a repository at Forsmark.

c) Relocation – The magnitude of the wind velocities and the distribution of the wind field affects the extent of relocation of primary producers and thus the location, e.g. wind is important for dispersion of pollen. In Forsmark, other factors such as nutrient and light availability are assumed to have larger effect on primary producers and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

d) Stimulation/inhibition – The atmosphere includes shading by clouds that may inhibit primary production. Temperature of the atmosphere may influence the pattern of settlement as different species thrive at different temperatures, oxygen conditions and humidity. Moreover, the temperature will affect the metabolism and secondary production of biota and that may be important for the distribution of radionuclides in the biotic community and exposure of man. Therefore, this interaction needs to be considered in a safety assessment for a repository at Forsmark.

5:7 Gas and local atmosphere affect **decomposers** by the processes a) Element supply, b) Exposure, and c) Stimulation/inhibition.

a) Element supply – Elements in the atmosphere are utilised by biota, e.g. oxygen for breathing. The amount of oxygen in the atmosphere is never limiting for biota and thus this interaction does not need to be considered in a safety assessment for a repository at Forsmark. Inhalation of radionuclides, on the other hand, is an important interaction but this is treated as exposure, see below.

b) Exposure – Exposure can either be external due to sources outside the body or internal due to sources inside the body. Concentration, location and type of radionuclides in surface waters, groundwater, regolith, and in the atmosphere, i.e. in all parts of the biosphere system, affect the external exposure of, and the radiologic and toxic effects on, biota. This interaction needs to be considered in a safety assessment for a repository at Forsmark.

c) Stimulation/inhibition – The temperature of the atmosphere may influence the pattern of settlement, as different species thrive at different temperatures, oxygen conditions and humidity. Moreover, the temperature will affect the metabolism and secondary production of biota and that may be important for the distribution of radionuclides in the biotic community and exposure of man. Therefore, this interaction needs to be considered in a safety assessment for a repository at Forsmark.

5:8 Gas and local atmosphere affect **filter feeders** by the process a) Element supply, b) Exposure, and c) Stimulation/inhibition.

a) Element supply – Elements in gas bubbles in water may be utilised as a supply by filter feeders. However, the element supply from gas bubbles should be minor compared with elements dissolved in water and this interaction is not important to consider in a safety assessment for a repository at Forsmark.

b) Exposure – Exposure can either be external due to sources outside the body or internal due to sources inside the body. Concentration, location and type of radionuclides in surface waters, groundwater, regolith, and in the atmosphere, i.e. in all parts of the biosphere system, affect the external exposure of, and the radiologic and toxic effects on, biota. This interaction needs to be considered in a safety assessment for a repository at Forsmark.

c) Stimulation/inhibition – The temperature of the atmosphere may influence the pattern of settlement, as different species thrive at different temperatures, oxygen conditions and humidity. Moreover, the temperature will affect the metabolism and secondary production of biota and that may be important for the distribution of radionuclides in the biotic community and exposure of man. However, filter feeders are situated within water and are more dependent on conditions within the water and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

5:9 Gas and local atmosphere affect **herbivores** by the process a) Element supply, b) Exposure, and c) Stimulation/inhibition.

a) Element supply – Elements in the atmosphere are utilised by biota, e.g. oxygen for breathing. The amount of oxygen in the atmosphere is never limiting for biota and thus this interaction does not need to be considered in a safety assessment for a repository at Forsmark. Inhalation of radionuclides, on the other hand, is an important interaction, but this is treated as exposure below and in 9:9.

b) Exposure – Exposure can either be external due to sources outside the body or internal due to sources inside the body. Concentration, location and type of radionuclides in surface waters, groundwater, regolith, and in the atmosphere, i.e. in all parts of the biosphere system, affect the external exposure of, and the radiologic and toxic effects on, biota. This interaction needs to be considered in a safety assessment for a repository at Forsmark.

c) Stimulation/inhibition – Temperature of the atmosphere may influence the pattern of settlement, as different species thrive at different temperatures, oxygen conditions and humidity. Moreover, the temperature will affect the metabolism and secondary production of biota and that may be important for the distribution of radionuclides in the biotic community and exposure of man. Therefore, this interaction needs to be considered in a safety assessment for a repository at Forsmark.

5:10 Gas and local atmosphere affect **carnivores** by the process a) Element supply, b) Exposure, and c) Stimulation/inhibition.

a) Element supply – Elements in the atmosphere are utilised by biota, e.g. oxygen for breathing. The amount of oxygen in the atmosphere is never limiting for biota and thus this interaction does not need to be considered in a safety assessment for a repository at Forsmark. Inhalation of radionuclides, on the other hand, is an important interaction, but this is treated as exposure below and in 10:10.

b) Exposure – Exposure can either be external due to sources outside the body or internal due to sources inside the body. Concentration, location and type of radionuclides in surface waters, groundwater, regolith, and in the atmosphere, i.e. in all parts of the biosphere system, affect the external exposure of, and the radiologic and toxic effects on, biota. This interaction needs to be considered in a safety assessment for a repository at Forsmark.

c) Stimulation/inhibition – The temperature of the atmosphere may influence the pattern of settlement, as different species thrive at different temperatures, oxygen conditions and humidity. Moreover, the temperature will affect the metabolism and secondary production of biota and that may be important for the distribution of radionuclides in the biotic community and exposure of man. Therefore, this interaction needs to be considered in a safety assessment for a repository at Forsmark.

5:11 Gas and local atmosphere affect **humans** by the processes a) Deposition b) Element supply, c) Exposure, and d) Stimulation/inhibition.

a) Deposition – Amounts of precipitation (rain and snow) influence the behaviour of humans. However, it is unlikely that amounts of precipitation in Forsmark will affect utilisation of the ecosystems. Thus, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

b) Element supply – Elements in the atmosphere are utilised by humans, e.g. oxygen for breathing. The amount of oxygen in the atmosphere is never limiting for human activities and thus this interaction does not need to be considered in a safety assessment for a repository at Forsmark. Inhalation of radionuclides, on the other hand, is an important interaction but this is treated as exposure below and in 11:11.

c) Exposure – Exposure can either be external due to sources outside the body or internal due to sources inside the body. Concentration, location and type of radionuclides in surface waters, groundwater, regolith, and in the atmosphere, i.e. in all parts of the biosphere system, affect the external exposure of, and the radiologic and toxic effects on, humans. Thus, this interaction needs to be considered in a safety assessment for a repository at Forsmark.

d) Stimulation/inhibition – The atmosphere may inhibit humans by toxins, smog, temperature and humidity. In addition, the magnitude of the wind velocities and the distribution of the wind field may affect humans. Assuming prevailing conditions, the atmosphere will have only a limited effect on human utilisation of the ecosystem. However, if taking into account future climate and temperatures, the temperature of the atmosphere may have effect on how humans are able to utilise the environment and thus be exposed to radionuclides. That part of this interaction needs to be considered in a safety assessment for a repository at Forsmark.

5:12 Gas and local atmosphere affect **external conditions** by the process a) Export.

a) Export – Elements, heat and radionuclides may be exported from the atmosphere to surrounding ecosystems or upper atmosphere layers.
   - The export of gas may be important for the transport of radionuclides from a local ecosystem, but it is assumed to be of little importance for the external conditions due to dilution in a large volume of the external atmosphere. Thus, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.
   - The export of heat (temperature) is regarded as quantitatively unimportant for the external conditions (i.e. surrounding ecosystem and atmosphere) and therefore this interaction does not need to be considered in a safety assessment for a repository at Forsmark.
   - The export of radionuclides out of the system most probably has a small effect on surrounding ecosystems and upper atmospheric layers due to dilution. However, the effect on the exporting system may be large, i.e. without export the concentrations in the exporting system could become high, and thus this interaction needs to be considered to achieve a realistic view of radionuclide concentrations in the ecosystems.

6:1 Primary producers affect **geosphere** by the process a) Intrusion.

a) Intrusion – Hypothetically, roots may penetrate into fractures in the solid rock and into the plugged and backfilled access tunnels. This could in turn affect rock structures, hydraulic conductivity, potential for erosion, physical and mechanical properties of the tunnels, and amounts of biological material. The root penetration depth of the terrestrial vegetation will generally be restricted to the upper 0.5 m, where the majority of roots are found. Deeper roots may be found, mainly in dry habitats such as pine forests on bedrock, but it is unlikely in Forsmark that roots will penetrate to repository depths (> 30 m) and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

6:2 Primary producers affect **regolith** by the processes a) Bioturbation, b) Convection, c) Death, d) Light-related processes, and e) Reactions.

a) Bioturbation – Root growth may affect the composition of the regolith and in aquatic ecosystems micro- primary producers within the regolith may influence the composition of the regolith by e.g. influencing oxygen concentrations. The composition of the regolith is important for transport and accumulation of radionuclides and this interaction needs to be considered in a safety assessment for a repository at Forsmark.

b) Convection – Vegetation can act as an insulator between the atmosphere and underlying water or regolith and thereby affect the transport of heat in the biosphere. In the aquatic ecosystems at Forsmark, the abundance of emergent macrophytes is low, but in the terrestrial ecosystems the vegetation may have an insulating effect. Other factors are assumed to have a greater influence on temperature. Therefore this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

c) Death – Primary producers affect the amount of dead organic matter in the regolith of the ecosystems when dying and by litter fall. This flux of organic matter may be important for the transport of radionuclides in ecosystems and needs to be considered in a safety assessment for a repository at Forsmark.

d) Light-related processes – The colour and structure of biota can affect the adsorption of radiation and thereby affect temperature of the regolith. The radiation absorption by biota in ecosystems will have relatively small effect on the temperature in the ecosystems compared to large scale climate changes and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

e) Reactions – Reactions within biota may be exo- or endothermic and influence temperature of the regolith. However, the metabolic heat of primary producers is limited compared with the heat absorption by e.g. the water bodies. Reactions also include degradation of toxicants by primary producers that affect the type and concentration of toxicants in the regolith and thereby affect the composition of the regolith. This may be important for toxicants but is of less importance for transport and accumulation of radionuclides. Thus, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

6:3 Primary producers affect **water in regolith** by the processes a) Convection, b) Excretion, c) Light-related processes, d) Reactions, e) Sorption/desorption, and f) Uptake.

a) Convection – Vegetation can act as an insulator between the atmosphere and underlying water or regolith and thereby affect the transport of heat in the biosphere. In the aquatic ecosystems at Forsmark, the abundance of emergent macrophytes is low, but in the terrestrial ecosystems the vegetation may have an insulating effect. Other factors (e.g. heat storage of surface water) are assumed to have a greater influence on temperature. Therefore, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

b) Excretion – primary producers rooted in or living in (e.g. microphytobenthos) the regolith in ecosystems may excrete water, radionuclides and other elements to the water in the regolith.
   - The effect of the excretion of water by primary producers on the amount of water in regolith in the ecosystems is minimal, since the excretion of water is very small compared with the water volume in the regolith and does not need to be considered in a safety assessment for a repository at Forsmark.
   - Excretion of radionuclides by primary producers affects the concentration of radionuclides in primary producers as well as in water in the regolith and needs to be considered in a safety assessment for a repository at Forsmark.
   - Excretion of elements and compounds by primary producers affects chemical parameters such as pH and concentrations of oxygen and carbon dioxide which are important for transport and accumulation of radionuclides. Therefore, this interaction needs to be considered in a safety assessment for a repository at Forsmark.

c) Light-related processes – The colour and structure of biota can affect the absorption of radiation and thereby affect temperature. The radiation absorption by biota in ecosystems will have relatively small effect on the temperature in the ecosystems compared to large scale climate changes and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

d) Reactions – Reactions within biota may be exo- or endothermic and influence the temperature of the water in the regolith. However, the metabolic heat of primary producers is limited compared with the heat absorption by e.g. the water bodies. Reactions also include degradation of toxicants by primary producers and affect the type and concentration of toxicants in the water in the regolith. This may be important for toxicants but is of less importance for the transport and accumulation of radionuclides. Thus, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

e) Sorption/desorption – Sorption and desorption of radionuclides by biota from water in the regolith may be important for the distribution of radionuclides between biota and regolith and therefore need to be considered in a safety assessment for a repository at Forsmark.

f) Uptake – Plant uptake of water, radionuclides and other elements may affect water in the regolith:
   - The uptake of water can significantly affect water in the regolith in terrestrial ecosystems. In agricultural land, plant uptake may result in a need for irrigation and this interaction needs to be considered in a safety assessment for a repository at Forsmark.
   - Uptake of radionuclides from water in the regolith by biota may be important for the distribution of radionuclides between biota and regolith. Thus, this interaction needs to be considered in a safety assessment for a repository at Forsmark.
   - Uptake by primary producers affects chemical parameters such as pH and concentrations of oxygen and carbon dioxide which is important for transport and accumulation of radionuclides. Therefore, this interaction needs to be considered in a safety assessment for a repository at Forsmark.

6:4 Primary producers affect **surface waters** by the processes a) Acceleration, b) Convection, c) Covering, d) Death, e) Excretion, f) Interception, g) Light-related processes, h) Reactions, i) Particle release/trapping, j) Sorption/desorption, and k) Uptake.

a) Acceleration – The type and amount of primary producers influence the movement of water, e.g. by overgrowing of a narrow sound or algae in surface waters. Other factors influencing water movements are probably more important than the reduction of velocities due to primary producers and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

b) Convection – Primary producers can affect transport of heat (i.e. convection of heat) as vegetation can act as an insulator between the atmosphere and underlying water or regolith. In the aquatic ecosystems at Forsmark, the abundance of emergent macrophytes is low, but in the terrestrial ecosystems the vegetation may have an insulating effect. Other factors (e.g. heat storage of surface water) are assumed to have a greater influence on temperature. Therefore the effect of primary producers on convection of heat in surface water does not need to be considered in a safety assessment for a repository at Forsmark.

c) Covering – The covering by biota in aquatic ecosystems in Forsmark is small since most primary producers are submerged. Also, in terrestrial ecosystems this interaction is assumed to be of minor importance for surface waters and it does not need to be considered in a safety assessment for a repository at Forsmark.

d) Death – Primary producers affect the amount of dead organic matter in surface waters of ecosystems mainly due to death, i.e. on a yearly basis the production of organisms that are not eaten contributes to the dead organic matter pool. This flux may be important for the redistribution of radionuclides in the ecosystem and needs to be considered in a safety assessment for a repository at Forsmark.

e) Excretion – Primary producers excrete water, radionuclides and other elements to surface water.
   - The effect of the excretion of water by primary producers on the amount of surface water in the ecosystems is minimal, since the excretion of water is very small compared with the surface water volume and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.
   - Excretion of radionuclides by primary producers affects the concentration of radionuclides in primary producers as well as in surface waters and needs to be considered in a safety assessment for a repository at Forsmark.
   - Excretion of elements and compounds by primary producers affects chemical parameters such as pH and concentrations of oxygen and carbon dioxide which is important for transport and accumulation of radionuclides. Therefore this interaction needs to be considered in a safety assessment for a repository at Forsmark.

f) Interception – Interception is the amount of precipitation that does not reach the ground but is retained on vegetation. In the aquatic ecosystems in the Forsmark area, most biota is submerged whereas in terrestrial ecosystems interception may affect the runoff. Runoff is important for transport and accumulation of radionuclides. In addition, in the case of irrigation, some of the water will be retained on vegetation due to interception and may thereby affect the amounts of radionuclides retained on vegetation. This interaction needs to be considered in a safety assessment for a repository at Forsmark.

g) Light-related processes – The colour and structure of biota can affect the adsorption of radiation and thereby affect temperature. The radiation absorption by biota in ecosystems will be very small compared with the radiation absorption by the other components, e.g. water bodies and regolith and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

h) Reactions – Reactions within biota may be exo- or endothermic and influence temperature. However, the metabolic heat of primary producers is limited compared with the heat absorption by e.g. the water bodies. Reactions also include degradation of toxicants by primary producers and affect the type and concentrations of toxicants in the surface waters. This may be important for toxicants but is of less importance for transport and accumulation of radionuclides. Thus, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

i) Particle release/trapping – The amount of particles in water is important for the transport of radionuclides attached to particle surfaces. Primary producers in terrestrial areas release large amounts of particles by pollen release, but this interaction goes via gas and local atmosphere (see below). In aquatic ecosystems, macrophytes may also release particles although most probably in smaller quantities. Particles may be attached to macrophytes in aquatic ecosystems, but this is most likely of minor significance compared with particle trapping by e.g. filter feeders (interaction 8:8) and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

j) Sorption/desorption – Sorption and desorption of radionuclides by biota is important for the transport and accumulation of radionuclides and therefore needs to be considered in a safety assessment for a repository at Forsmark.

k) Uptake – Plant uptake of water, radionuclides and other elements may affect surface waters.
   - Terrestrial plants take up most of their water from water in the regolith where the uptake of water can significantly affect water in the regolith. Uptake of surface water by primary producers in lakes, streams and marine basins on the other hand is very small compared with the volumes of the water bodies and does not need to be considered in a safety assessment for a repository at Forsmark.
   - Uptake of radionuclides from surface waters by biota may be important for the distribution of radionuclides between biota and the surface waters. Thus, this interaction needs to be considered in a safety assessment for a repository at Forsmark.
   - Uptake by primary producers affects chemical parameters such as pH and concentrations of oxygen and carbon dioxide which is important for transport and accumulation of radionuclides. Therefore, this interaction needs to be considered in a safety assessment for a repository at Forsmark.

6:5 Primary producers affect **gas and local atmosphere** by the processes a) Acceleration, b) Covering c) Excretion, d) Light-related processes, e) Reactions, f) Particle release/trapping, g) Sorption/desorption, and h) Uptake.

a) Acceleration – The type, amount and location of primary producers determine the degree of sheltering and influence thereby wind directions and velocities. This can have an effect on atmospheric exchange and needs to be considered in a safety assessment for a repository at Forsmark.

b) Covering – The covering by biota in aquatic ecosystems in Forsmark is small, since most primary producers are submerged. Also in terrestrial ecosystems this interaction is assumed to be of minor importance for the atmosphere and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

c) Excretion – Primary producers affect the gas and local atmosphere by excreting radionuclides and other elements.
   - Excretion of radionuclides by primary producers affects the concentration of radionuclides in primary producers as well as in the atmosphere and needs to be considered in a safety assessment for a repository at Forsmark.

- Primary producers excrete oxygen during photosynthesis and terrestrial primary producers have a direct impact on the gas content in the local atmosphere. In aquatic ecosystems, the excretion of gas to the water volume may influence the amounts of gas in surface waters and thereby transport of gases across the air-water interface. Accordingly, this interaction needs to be considered in a safety assessment for a repository at Forsmark.

d) Light-related processes – The colour and structure of biota can affect the adsorption of radiation and thereby affect temperature. The radiation absorption by biota in ecosystems will have relatively small effect on the temperature in the ecosystems compared to large scale climate changes and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

e) Reactions – Reactions within biota may be exo- or endothermic and influence the temperature of the atmosphere. However, the metabolic heat of primary producers is limited compared with the heat absorption by e.g. the water bodies and therefore this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

f) Particle release/trapping – In terrestrial ecosystems, particle release and trapping may be frequent (e.g. pollen release) although the importance for transfer and accumulation of radionuclides is considered as minor. In aquatic ecosystems, the importance is even less. Emergent aquatic macrophytes can spread particles with the wind, but most aquatic macrophytes are submerged and the amount of particles released to the atmosphere is small. Therefore, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

g) Sorption/desorption – Sorption and desorption of radionuclides by biota is important for the transport and accumulation of radionuclides and therefore needs to be considered in a safety assessment for a repository at Forsmark.

h) Uptake – Primary producers may take up radionuclides and other elements from the atmosphere.
   - Uptake of radionuclides from atmosphere by biota may be important for the distribution of radionuclides between biota and atmosphere. Thus, this interaction needs to be considered in a safety assessment for a repository at Forsmark.
   - Plants take up carbon dioxide and other elements (e.g. iodine) and release oxygen in terrestrial and aquatic ecosystems. In aquatic ecosystems, the uptake of gas from the water volume may influence the amounts of gases in surface waters and thereby transport of gases across the air-water interface. Accordingly, this interaction needs to be considered in a safety assessment for a repository at Forsmark.

6:6 Primary producers is a diagonal element that is further described in Chapter 4. Primary producers is internally affected by the features Geometry, Material composition, Stage of succession, Temperature, Water composition and Radionuclide inventory. Primary producers affect each other by the following processes: a) Exposure, b) Growth, c) Habitat supply, d) Light-related processes, e) Primary production, f) Radioactive decay, g) Reactions, and h) Stimulation/inhibition.

a) Exposure – Exposure can either be external due to sources outside the body or internal due to sources inside the body. Concentration, location and type of radionuclides in surface waters, regolith, and in the atmosphere, i.e. in all parts of the biosphere system, affect the external exposure of, and the radiologic and toxic effects on, biota. Concentration within biota affects the internal dose. The effects on organisms may include cellular death and affect biomass and production of primary producers, and this interaction needs to be considered in a safety assessment for a repository at Forsmark.

b) Growth – Growth can potentially lower the concentration of radionuclides in primary producers due to dilution of radionuclides in biomass and needs to be considered in a safety assessment for a repository at Forsmark.

c) Habitat supply – The biomass of epiphytic flora on terrestrial vegetation is small in relation to the biomass of the non-epiphytic vegetation. In aquatic ecosystems, macrophytes are often colonised by epiphytic algae and can in some systems make up a substantial part of primary producers. As long as the majority of primary production is considered in the assessment, this interaction is assumed to have small effect on the transport of radionuclides in ecosystems and therefore does not need to be considered in a safety assessment for a repository at Forsmark.

d) Light-related processes – The type, amount and location of primary producers determine the degree of adsorption and reflection of radiation and influence thereby the temperature in the biosphere. The radiation absorption by biota in aquatic ecosystems will be very small compared with the radiation absorption by the water body and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

e) Primary production – Primary production is the fixation of carbon by primary producers mediated by photosynthesis. This is an important process that generates biomass which is fundamental for the existence of the primary producers. Primary production is important for the incorporation of radionuclides (especially C-14) into biota and this interaction needs to be considered in a safety assessment for a repository at Forsmark.

f) Radioactive decay – Radionuclides in the different biosphere components undergo radioactive decay where they transform into other radionuclides or form stable isotopes. Decay of radionuclides is important to consider in estimating the amounts of different radionuclides in the biosphere and this process needs to be considered in a safety assessment for a repository at Forsmark.

g) Reactions – Reactions within biota may be exo- or endothermic and influence the temperature of primary producers. However, the metabolic heat of vegetation in aquatic ecosystems is limited compared with the heat absorption by the water body. Reactions can also have an effect on the distribution and transport of radionuclides within biota but this is generally covered by the use of CR values in which this is included in safety assessments. Therefore this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

h) Stimulation/inhibition – Primary producers may stimulate each other e.g. by sexual reproduction or inhibit each other by e.g. resource competition. This interaction does not directly influence the transport of radionuclides in the ecosystem and therefore does not need to be considered in a safety assessment for a repository at Forsmark. Nevertheless it is often implicitly included in safety assessments as long as site data is used, which reflects the situation with stimulation/inhibition at a site.

6:7 Primary producers affect **decomposers** by the processes a) Habitat supply, and b) Stimulation/inhibition.

a) Habitat supply – Macrophytes are often colonised by epiphytic bacteria. Primary producers may affect the decomposers by the quality of the litter. These interactions are considered to be of relatively low importance to the transport of radionuclides in the ecosystems and therefore do not need to be considered in a safety assessment for a repository at Forsmark.

b) Stimulation/inhibition – Primary producers may stimulate decomposers by e.g. providing a substrate for epiphytic bacteria or they may inhibit decomposers by competition for resources e.g. phytoplankton and bacterioplankton competing for dissolved nitrogen and phosphorus. This interaction does not directly influence the transport of radionuclides in the ecosystem and therefore does not need to be considered in a safety assessment for a repository at Forsmark.

6:8 Primary producers affect **filter feeders** in aquatic ecosystems by the processes a) Food supply, b) Habitat supply, and c) Stimulation/inhibition.

a) Food supply – Primary producers function as food for filter feeders (e.g. the consumption of phytoplankton). This may be an important transfer pathway for radionuclides and the interaction needs to be considered in a safety assessment for a repository at Forsmark.

b) Habitat supply – Macrophytes can be colonised by filtering species of hydrozoans or small mussels. This interaction does not directly influence the transport of radionuclides in the ecosystem and therefore does not need to be considered in a safety assessment for a repository at Forsmark.

c) Stimulation/inhibition – Primary producers may inhibit filter feeders by e.g. space competition or toxin production. This interaction does not directly influence the transport of radionuclides in the ecosystem and therefore does not need to be considered in a safety assessment for a repository at Forsmark.

6:9 Primary producers affect **herbivores** by the processes a) Food supply, b) Habitat supply, and c) Stimulation/inhibition.

a) Food supply – Primary producers function as food for herbivores. This may be an important transfer pathway for radionuclides and the interaction needs to be considered in a safety assessment for a repository at Forsmark.

b) Habitat supply – Primary producers may be colonised by e.g. herbivorous snails. This interaction does not directly influence the transport of radionuclides in the ecosystem and therefore does not need to be considered in a safety assessment for a repository at Forsmark.

c) Stimulation/inhibition – Primary producers may stimulate herbivores by e.g. providing substrate and a food source of specific quality and palatability. Primary producers may inhibit herbivores by e.g. toxin production. This interaction does not influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in a safety assessment for a repository at Forsmark.

6:10 Primary producers affect **carnivores** by the process a) Stimulation/inhibition.

a) Stimulation/inhibition – Primary producers may stimulate carnivores by e.g. providing sheltered areas for reproduction. Primary producers may inhibit carnivores by e.g. toxin production. This interaction does not influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in a safety assessment for a repository at Forsmark.

6:11 Primary producers affect **humans** by the processes a) Food supply, b) Material supply, and c) Stimulation/inhibition.

a) Food supply – Humans may consume primary producers and therefore the primary production that may be used as food by humans needs to be considered in a safety assessment for a repository at Forsmark.

b) Material supply – Primary producers may be utilised as a material in building houses (wood and reed in thatching) and in gaining energy (burning peat or wood). The effect on exposure to humans will most probably be small but, to assure that, this interaction should be considered in a safety assessment for a repository at Forsmark.

c) Stimulation/inhibition – Primary producers may affect humans, e.g. toxic algal blooms in aquatic ecosystems. However, inhibition of humans would lead to less utilisation of the ecosystem and thereby less risk of exposure to potential radionuclides. However, for long time periods it can be difficult to, with certainty, determine inhibition and if no inhibition is assumed this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

6:12 Primary producers affect **external conditions** by the process a) Export.

a) Export – In aquatic systems the continuous outflow of pelagic organisms can be considerable. In terrestrial systems the export is more occasional, e.g. pollen release. In a radionuclide perspective, export may be important for the ecosystem the biota leave, since the exporting biota may contain radionuclides and thereby there might be a dilution of radionuclides in the ecosystem. The effect on the receiving ecosystem (i.e. external conditions) should, in contrast, in most cases be smaller (due to dilution in downstream aquatic objects). However, large amounts may be harvested and used as e.g. animal food or as manure which could concentrate the radionuclides in a smaller area and give rise to higher exposure to humans. Thus, this interaction needs to be considered in a safety assessment for a repository at Forsmark.

7:1 Decomposers affect **geosphere** by the process a) Intrusion.

a) Intrusion – Macro-decomposers can only enter the repository in the geosphere if the passage is open to the repository. However, even if the passage is open it is unlikely that macrodecomposers would thrive at repository depths (i.e. below 30 m). Micro-decomposers, on the other hand, are assumed to exist in the repository but although they may be important to consider in the safety assessment for the geosphere they are not assumed to move between the biosphere and the repository and are not important to consider in the biosphere part of a safety assessment for a repository at Forsmark.

7:2 Decomposers affect **regolith by** the processes a) Bioturbation, b) Consumption, c) Convection, d) Death, e) Decomposition, f) Excretion, g) Light-related processes, and h) Reactions.

a) Bioturbation – Decomposers affect the regolith in ecosystems by bioturbation (by e.g. worms). Bioturbation affects the physical properties and the chemical composition of the upper regolith which may be important for the transport of radionuclides and thus needs to be considered in a safety assessment for a repository at Forsmark.

b) Consumption – Decomposers may consume large quantities of organic compounds in the regolith and thereby affect the composition of the regolith as well as the distribution of radionuclides between decomposer and regolith. This interaction needs to be considered in a safety assessment for a repository at Forsmark.

c) Convection – Organisms can act as an insulator between the atmosphere and underlying water and regolith thereby affecting the transport of heat in the regolith. However, the density of decomposers is small and other factors will have greater impact on temperature in the ecosystems. Thus, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

d) Death – Decomposers affect the amount of dead organic matter in the regolith of ecosystems mainly when dying or via faeces. This flux may be important for the redistribution of radionuclides in the ecosystem and this interaction needs to be considered a safety assessment for a repository at Forsmark.

e) Decomposition – The type and efficiency of decomposers affects the content and quality of organic material in the regolith and this interaction needs to be considered in a safety assessment for a repository at Forsmark.

f) Excretion – Decomposers situated in the upper sediments may particles, radionuclides and other elements and compounds into the regolith.
   - The effect of the excretion of particles into the regolith in the ecosystems is minimal compared to the large amounts of regolith and does not need to be considered in a safety assessment for a repository at Forsmark.
   - Excretion of radionuclides by decomposer may affect the concentration of radionuclides in decomposers as well as in regolith and needs to be considered in a safety assessment for a repository at Forsmark.
   - Excretion of elements and compounds by decomposer affects chemical parameters such as pH and concentrations of oxygen and carbon dioxide which are important for transport and accumulation of radionuclides. Therefore, this interaction needs to be considered in a safety assessment for a repository at Forsmark.

g) Light-related processes – The colour and structure of biota can affect the adsorption of radiation and thereby affect temperature. The radiation absorption by biota in ecosystems will have relatively small effect on the temperature in the ecosystems compared to large scale climate changes and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

h) Reactions – Reactions within biota may be exo- or endothermic and influence the temperature of the regolith. However, the metabolic heat of decomposers is limited compared with the heat absorption by e.g. the water bodies. Reactions also include degradation of toxicants by decomposers and affect the type and concentration of toxicants in the regolith. This may be important for toxicants but is of less importance for transport and accumulation of radionuclides. Thus, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

7:3 Decomposers affect **water in regolith** by the processes a) Convection, b) Decomposition, c) Excretion, d) Light-related processes, e) Reactions, f) Sorption/desorption, and g) Uptake.

a) Convection – Organisms can act as an insulator between atmosphere and underlying water and regolith thereby affecting the transport of heat in water in regolith. However, the density of decomposers is small and other factors will have greater impact on temperature in the ecosystems. Thus, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

b) Decomposition – The type and efficiency of decomposers may influence the water content in the regolith as decomposers release water from pores and cells. Decomposition also affects the organic content of the degraded matter, but this is treated in interaction (7:2). The effect of decomposition on the amount of water in regolith in aquatic and mire ecosystems is minimal, since the release of water is very small compared to the water volume. Thus, this interaction does not need to be considered in the radionuclide modelling.

c) Excretion – Decomposers in and on the regolith may excrete water, radionuclides and other elements and compounds into the regolith.
   - The effect of the excretion of water by decomposers on the amount of water in regolith in the ecosystems is minimal, since the excretion of water is very small compared to the water volume in the regolith and does not need to be considered in a safety assessment for a repository at Forsmark.
   - Excretion of radionuclides by decomposers affects the concentration of radionuclides in decomposers as well as in water in the regolith and needs to be considered in a safety assessment for a repository at Forsmark.
   - Excretion of elements and compounds by decomposers affects chemical parameters such as pH and concentrations of oxygen and carbon dioxide which are important for transport and accumulation of radionuclides. Therefore, this interaction needs to be considered in a safety assessment for a repository at Forsmark.

d) Light-related processes – The colour and structure of biota can affect the adsorption of radiation and thereby affect the temperature in water in the regolith. The radiation absorption by biota in ecosystems will have relatively small effect on the temperature in the ecosystems compared to large scale climate changes and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

e) Reactions – Reactions within biota may be exo- or endothermic and influence the temperature of water in the regolith. However, the metabolic heat of decomposers is limited compared with the heat absorption by e.g. the water bodies. Reactions also include degradation of toxicants by decomposers and affect the type and concentration of toxicants in the water in the regolith. This may be important for toxicants but is of less importance for transport and accumulation of radionuclides. Thus, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

f) Sorption/desorption – Sorption and desorption of radionuclides by biota is important for the transport and accumulation of radionuclides and therefore needs to be considered in a safety assessment for a repository at Forsmark.

g) Uptake – Decomposers (e.g. bacteria) living in the regolith take up water, radionuclides and other elements from the regolith.
   - The effect of the uptake of water by decomposers on the amount of water in regolith in aquatic and mire ecosystems is minimal, since the uptake of water is very small compared with the water volume. Thus, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.
   - Uptake of radionuclides from water in the regolith by biota may be important for the distribution of radionuclides between biota and regolith. Thus, this interaction needs to be considered in a safety assessment for a repository at Forsmark.
   - Uptake by decomposers affects chemical parameters such as pH and concentrations of oxygen and carbon dioxide which are important for transport and accumulation of radionuclides. Therefore, this interaction needs to be considered in a safety assessment for a repository at Forsmark.

7:4 Decomposers affect **surface waters** by the processes a) Acceleration, b) Consumption, c) Death, d) Decomposition, e) Excretion, f) Light-related processes, g) Movement, h) Particle release/trapping, i) Reactions, j) Sorption/desorption, and k) Uptake.

a) Acceleration – The type and amount of decomposers attached to any surface may influence the properties of the surface and thereby water movement. Other forcing factors will have a much larger effect on surface water movement than decomposers and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

b) Consumption – Decomposers may consume large quantities of organic compounds in water and thereby affect the water composition and also the transport and accumulation of radionuclides. Therefore this interaction needs to be considered in a safety assessment for a repository at Forsmark.

c) Death – Decomposers affect the amount of dead organic matter in water mainly when dying. This flux may be important for the redistribution of radionuclides in the ecosystem and needs to be considered in a safety assessment for a repository at Forsmark.

d) Decomposition – Decomposers release water and elements during decomposition.
   - The effect on the amounts of surface water by decomposition is insignificant considering the large water volumes in aquatic ecosystems. The effect of this interaction on temporarily occurring surface waters in terrestrial ecosystems is minimal for the same reason, therefore this interaction does not need to be considered in a safety assessment for a repository at Forsmark.
   - Decomposition may influence the water composition by altering the structure of organic compounds. This may influence the transport and accumulation of radionuclides, e.g. the amount of organic matter that is left in water and contributes to accumulation of elements and radionuclides and this interaction needs to be considered in a safety assessment for a repository at Forsmark.

e) Excretion – Decomposers in and on the regolith may excrete water, radionuclides and other elements and compounds into surface water.
   - The effect of the excretion of water by decomposers on the amount of surface water in the ecosystems is minimal, since the excretion of water is very small compared to surface water volumes and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.
   - Excretion of radionuclides by decomposers affects the concentration of radionuclides in decomposers as well as in surface water and needs to be considered in a safety assessment for a repository at Forsmark.
   - Excretion of elements and compounds by decomposers affects chemical parameters such as pH and concentrations of oxygen and carbon dioxide which are important for transport and accumulation of radionuclides. Therefore, this interaction needs to be considered in a safety assessment for a repository at Forsmark.

f) Light-related processes – The colour and structure of biota can affect the adsorption of radiation and thereby affect temperature. The radiation absorption by biota in ecosystems will have relatively small effect on the temperature in the ecosystems compared to large scale climate changes and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

g) Movement – The movement of organisms in surface waters may have an influence on the surface water movement. However, decomposers are relatively small and will not significantly affect flow in a water body. Thus, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

h) Particle release/trapping – Decomposers may release or trap particles in water. The amount of particles in water is important for the transport of radionuclides. However, decomposers are assumed to have relatively small impact on particle release and trapping in surface waters compared with filter feeders and this interaction does not need to be considered.

i) Reactions – Reactions within biota may be exo- or endothermic and influence temperature. However, the metabolic heat of decomposers is limited compared with the heat absorption by e.g. the water bodies. Reactions also include degradation of toxicants by decomposers and affect the type and concentrations of toxicants in surface waters. This may be important for toxicants but is of less importance for transport and accumulation of radionuclides. Thus, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

j) Sorption/desorption – Sorption and desorption of radionuclides by biota is important for the transport and accumulation of radionuclides and, therefore, needs to be considered in a safety assessment for a repository at Forsmark.

k) Uptake – Decomposers (e.g. bacteria) living in the regolith take up water, radionuclides and other elements from the regolith.
   - The effect of the uptake of water by decomposers on the amount of surface water in ecosystems is minimal, since the uptake of water is very small compared to the water volumes of surface water bodies. Thus, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.
   - Uptake of radionuclides from surface waters by biota may be important for the distribution of radionuclides between biota and regolith. Thus, this interaction needs to be considered in a safety assessment for a repository at Forsmark.

- Uptake by decomposers affects chemical parameters such as pH and concentrations of oxygen and carbon dioxide which are important for transport and accumulation of radionuclides. Therefore, this interaction needs to be considered in a safety assessment for a repository at Forsmark.

7:5 Decomposers affect **gas and local atmosphere** by the processes a) Excretion, b) Light-related processes, c) Particle release/trapping, d) Reactions, e) Sorption/desorption, and f) Uptake.

a) Excretion – Decomposers excrete radionuclides and other elements to the atmosphere and gas phase of water.
   - Excretion of radionuclides by decomposers affects the concentration of radionuclides in decomposers as well as in the atmosphere and needs to be considered in a safety assessment for a repository at Forsmark.
   - Decomposers excrete gases, mainly carbon dioxide and methane, and thereby influence gas and local atmosphere. As an example, large amounts of methane have been found in sediments of lakes and shallow bays during site investigations in Forsmark (Borgiel 2004), and a large proportion of this gas is likely the result of decomposing organic regolith (Karlsson and Nilsson 2007). Thus, this interaction needs to be considered in a safety assessment for a repository at Forsmark.

b) Light-related processes – The colour and structure of biota can affect the adsorption of radiation and thereby affect temperature. The radiation absorption by biota in ecosystems will have relatively small effect on the temperature in the ecosystems compared to large scale climate changes and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

c) Particle release/trapping – Decomposers may affect the amount of particles in the atmosphere, e.g. by trapping on slimy surfaces and by the production and release of spores. However, particle release and trapping by decomposers are insignificant compared with particle release and trapping by primary producers and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

d) Reactions – Reactions within biota may be exo- or endothermic and influence temperature. However, the metabolic heat of decomposers is limited compared with the heat absorption by e.g. the water bodies and therefore this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

e) Sorption/desorption – Sorption and desorption of radionuclides by biota is important for the transport and accumulation of radionuclides and therefore needs to be considered in a safety assessment for a repository at Forsmark.

f) Uptake – Decomposers take up radionuclides and other elements from the atmosphere and gas phase.
   - Uptake of radionuclides from atmosphere by biota may be important for the distribution of radionuclides between biota and atmosphere. Thus, this interaction needs to be considered in a safety assessment for a repository at Forsmark.
   - Decomposers take up mainly oxygen from the atmosphere and gas phase of water, but also other chemical compounds are utilised, e.g. by methanotrophs. In terrestrial ecosystems, uptake of elements and compounds by decomposers should have minor effect on the gas and local atmosphere. In aquatic ecosystems on the other hand, the uptake of oxygen may cause oxygen deficit, especially during stratified conditions in winter. This may then limit the distribution of biota in aquatic ecosystems and therefore this interaction needs to be considered in a safety assessment for a repository at Forsmark.

7:6 Decomposers affect **primary producers** by the process a) Stimulation/inhibition.

a) Stimulation/inhibition – Decomposers may inhibit primary producers by e.g. resource competition, whereas they stimulate primary producers mainly indirectly by influencing water composition and regolith characteristics in aquatic ecosystems. In terrestrial ecosystems effects from fungus biodiversity that increases mineralisation and the presence of myccorrhizal species can both directly affect primary production. However, this interaction is less studied in wetlands. This interaction does not significantly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in a safety assessment for a repository at Forsmark.

7:7 Decomposers is a diagonal element that is further described in Chapter 4. Decomposers is internally affected by the features Geometry, Material composition, Stage of succession, Temperature, Water composition and Radionuclide inventory. Decomposers affect each other by the following processes a) Exposure, b) Growth, c) Radioactive decay, and d) Stimulation/inhibition.

a) Exposure – Exposure can either be external due to sources outside the body or internal due to sources inside the body. Concentration, location and type of radionuclides in surface waters, regolith, and in the atmosphere, i.e. in all parts of the biosphere system, affect the external exposure of, and the radiologic and toxic effects on, biota. Concentrations within biota affect the internal dose. The effects on organisms may include cellular death and affect biomass of decomposer, and this interaction needs to be considered in a safety assessment for a repository at Forsmark.

b) Growth – Growth can potentially lower the concentrations of radionuclides in biota due to dilution in biomass and needs to be considered in a safety assessment for a repository at Forsmark.

c) Radioactive decay – Radionuclides in the different biosphere components undergo radioactive decay where they transform into other radionuclides or form stable isotopes. Decay of radionuclides is important to consider in estimating the amounts of different radionuclides in the biosphere and this process needs to be considered in a safety assessment for a repository at Forsmark.

d) Stimulation/inhibition – Decomposers may stimulate each other by e.g. mating and they may inhibit each other by e.g. resource and space competition. This interaction does not significantly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in a safety assessment for a repository at Forsmark.

7:8 Decomposers affect **filter feeders** in the aquatic ecosystems by the processes a) Food supply, and b) Stimulation/inhibition.

a) Food supply – Decomposers may function as a food source for filter feeders (e.g. filtering of pelagic bacteria). This may be important for the transport of radionuclides and needs to be considered in a safety assessment for a repository at Forsmark.

b) Stimulation/inhibition – Decomposers may stimulate filter feeders by e.g. providing food of different quality. Decomposers may inhibit filter feeders by e.g. competition for substrate and resources. This interaction does not directly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in a safety assessment for a repository at Forsmark.

7:9 Decomposers affect **herbivores** by the process a) Stimulation/inhibition.

a) Stimulation/inhibition – Decomposers may inhibit herbivores by e.g. substrate competition. This interaction does not directly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in a safety assessment for a repository at Forsmark.

7:10 Decomposers affect **carnivores** by the processes a) Food supply, and b) Stimulation/inhibition.

a) Food supply – Decomposers may function as a food source for carnivores (e.g. consumption of macro-decomposers, bacteria and fungi). This may be important for the transport of radionuclides and needs to be considered in a safety assessment for a repository at Forsmark.

b) Stimulation/inhibition – Decomposers may stimulate carnivores by e.g. providing food of different quality or they may inhibit carnivores by e.g. competition for space. This interaction does not directly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in a safety assessment for a repository at Forsmark.

7:11 Decomposers affect **humans** by the processes a) Food supply, b) Material supply, and c) Stimulation/inhibition.

a) Food supply – Decomposers, e.g. fungi and crayfish (that are omnivorous and thus a mix of decomposers, herbivores and carnivores), may function as a food source for humans and therefore this interaction needs to be considered in a safety assessment for a repository at Forsmark.

b) Material supply – Material use of decomposers by humans is small and the supply of decomposers for human utilisation does not need to be considered in a safety assessment for a repository at Forsmark.

c) Stimulation/inhibition – There are no decomposers that are likely to stimulate or inhibit human utilisation of the environment and therefore this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

7:12 Decomposers affect **external conditions** by the process a) Export.

a) Export – Decomposers may leave the ecosystem which besides the decomposers themselves may include an export of radionuclides and heat.
   - Export may be important for the ecosystem the biota leave since the exported biota may contain radionuclides and thereby there might be a dilution of radionuclides in the ecosystem. The effect on the receiving ecosystem should, in contrast, in most cases be small (due to dilution in downstream objects). This is especially true for organisms that are not transported to a large degree and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.
   - The export of heat is regarded as quantitatively unimportant for the external conditions (i.e. surrounding ecosystem and atmosphere) and therefore this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

Since filter feeders only are present in aquatic ecosystems the following interactions, 8:1–8:12, are only valid for aquatic ecosystems and do not treat interactions in terrestrial ecosystems.

8:1 Filter feeders affect the **geosphere** in aquatic ecosystems by the process a) Intrusion.

a) Intrusion – Filter feeders normally penetrate at most a few decimetres through a sediment surface and it is highly unlikely that they would intrude to repository depth. Therefore, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

8:2 Filter feeders affect the **regolith** in aquatic ecosystems by the processes a) Bioturbation, b) Convection, c) Death, d) Light-related processes, e) Reactions, and f) Sorption/desorption.

a) Bioturbation – Filter feeders (e.g. bivalves) may affect the regolith by bioturbation which may alter the physical properties and chemical composition of the upper regolith. In the aquatic ecosystem at Forsmark, the filter feeders are scattered in space and their effect on the regolith is relatively small. Therefore, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

b) Convection – Organisms can act as an insulator between the atmosphere and underlying water and regolith thus affecting the transport of heat in the regolith. However, other factors will have greater impact on temperature in the ecosystems. Thus this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

c) Death – Filter feeders affect the amount of dead organic matter in the regolith in aquatic ecosystems mainly when dying. This flux may be important for the redistribution of radionuclides in the ecosystem and therefore needs to be considered in a safety assessment for a repository at Forsmark.

d) Light-related processes – The colour and structure of biota can affect the adsorption of radiation and thereby affect temperature. The radiation absorption by filter feeders in ecosystems will be very small compared to the radiation absorption by other components, e.g. water bodies and regolith, and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

e) Reactions – Reactions within biota may be exo- or endothermic and influence temperature. However, the metabolic heat of filter feeders is limited compared with the heat absorption by e.g. the water bodies. Reactions also include degradation of toxicants by filter feeders and affect the type and concentration of toxicants in the regolith. This may be important for toxicants but is of less importance for transport and accumulation of radionuclides. Thus, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

f) Sorption/desorption – Sorption and desorption of radionuclides by biota is important for the transport and accumulation of radionuclides and therefore needs to be considered in a safety assessment for a repository at Forsmark.

8:3 Filter feeders affect **water in regolith** by the processes a) Convection, b) Excretion, c) Light-related processes, d) Reactions, e) Sorption/desorption, and f) Uptake.

a) Convection – Organisms can act as an insulator between atmosphere and underlying water and regolith thus affecting the transport of heat in the biosphere. However, other factors will have greater impact on temperature in the ecosystems. Thus this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

b) Excretion – Filter feeders situated in the upper sediments may excrete water, radionuclides and other elements and compounds into the regolith.
   - The effect of the excretion of water by filter feeders on the amount of water in regolith in the ecosystems is minimal, since the excretion of water is very small compared to the water volume in the regolith and does not need to be considered in a safety assessment for a repository at Forsmark.
   - Excretion of radionuclides by filter feeders affects the concentration of radionuclides in filter feeders as well as in water in regolith and needs to be considered in a safety assessment for a repository at Forsmark.
   - Excretion of elements and compounds by filter feeders affects chemical parameters such as pH and concentrations of oxygen and carbon dioxide which are important for transport and accumulation of radionuclides. Therefore, this interaction needs to be considered in a safety assessment for a repository at Forsmark.

c) Light-related processes – The colour and structure of biota can affect the adsorption of radiation and thereby affect temperature. The radiation absorption by biota in ecosystems will be very small compared with the radiation absorption by other components, e.g. water bodies and regolith, and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

d) Reactions – Reactions within biota may be exo- or endothermic and influence temperature. However, the metabolic heat of filter feeders is limited compared with the heat absorption by e.g. the water bodies. Reactions also include degradation of toxicants by filter feeders and affect the type and concentration of toxicants in water in the regolith. This may be important for toxicants but is of less importance for transport and accumulation of radionuclides. Thus, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

e) Sorption/desorption – Sorption and desorption of radionuclides by biota is important for the transport and accumulation of radionuclides and therefore needs to be considered in a safety assessment for a repository at Forsmark.

f) Uptake – Filter feeders living in the regolith take up water, radionuclides and other elements from the regolith.
   - The effect of the uptake of water by filter feeders on the amount of water in the regolith is minimal, since the uptake of water is very small compared with the water volume. Thus, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.
   - Uptake of radionuclides from water in the regolith by biota may be important for the distribution of radionuclides between biota and regolith. Filter feeders mainly filter surface water and not water present in the regolith and thus this interaction does not need to be considered in a safety assessment for a repository at Forsmark.
   - Uptake by filter feeders can potentially affect chemical parameters such as pH and concentrations of oxygen and carbon dioxide which are important for transport and accumulation of radionuclides. However, filter feeders mainly filter surface water and not water present in the regolith and thus this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

8:4 Filter feeders affect **surface waters** in aquatic ecosystems by the processes a) Acceleration, b) Consumption c) Death, d) Excretion, e) Light-related processes, f) Movement, g) Particle release/trapping, h) Reactions, i) Sorption/desorption, and j) Uptake.

a) Acceleration – The type and amount of filter feeders attached to surfaces may hypothetically influence the properties of the surfaces and thereby water movement. In lakes and in the sea, other forcing factors will have greater effects on the surface-water movement than filter feeders and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

b) Consumption – Filter feeders can consume organic particles in the water. This is important for the distribution of radionuclides between water and biota and needs to be considered in a safety assessment for a repository at Forsmark.

c) Death – Filter feeders affect the amount of dead organic matter in water mainly when dying. This flux may be important for the redistribution of radionuclides in the ecosystem and therefore needs to be considered in a safety assessment for a repository at Forsmark.

d) Excretion – Filter feeders may excrete water, radionuclides and other elements and compunds into surface waters:
   - The excretion of water by filter feeders will have a small effect on the amount of surface water in the aquatic ecosystems, since the excretion of water is very small compared with the water volume in the regolith and does not need to be considered in a safety assessment for a repository at Forsmark.
   - Excretion of radionuclides by filter feeders affects the concentration of radionuclides in filter feeders as well as in surface waters and needs to be considered in a safety assessment for a repository at Forsmark.
   - Excretion of elements and compounds by filter feeders affects chemical parameters such as pH and concentrations of oxygen and carbon dioxide which are important for transport and accumulation of radionuclides. Therefore, this interaction needs to be considered in a safety assessment for a repository at Forsmark.

e) Light-related processes – The colour and structure of biota can affect the absorption of radiation and thereby affect temperature. The radiation absorption by filter feeders in aquatic ecosystems will be very small compared with the radiation absorption by the water body, and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

f) Movement – Filter feeders influence the water flow by filtering water. However, compared with the turnover rates of water, the effect of filter feeders is small at Forsmark, since the abundance of filter feeders is relatively low and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

g) Particle release/trapping – The amount of particles in water is important for the transport of radionuclides attached to particle surfaces. Filter feeders can trap large amounts of particles from the water by filtering thereby affecting water composition and attributes such as turbidity (Soto and Mena 1999, Wilkinson et al. 2008). Filter feeders can release particles by e.g. releasing offspring. Thus, this interaction needs to be considered in in a safety assessment for a repository at Forsmark.

h) Reactions – Reactions within biota may be exo- or endothermic and influence temperature. However, the metabolic heat of filter feeders is limited compared with the heat absorption by e.g. the water bodies. Reactions also include degradation of toxicants by filter feeders and affect the type and concentration of toxicants in surface waters. This may be important for toxicants but is of less importance for transport and accumulation of radionuclides. Thus, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

i) Sorption/desorption – Sorption and desorption of radionuclides by biota is important for the transport and accumulation of radionuclides and therefore needs to be considered in a safety assessment for a repository at Forsmark.

j) Uptake – Filter feeders take up water, radionuclides and other elements from surface waters.
   - The effect of the uptake of water by filter feeders on the amount of surface water is minimal, since the uptake of water is very small compared with the water volume. Thus, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.
   - Uptake of radionuclides from surface waters by biota may be important for the distribution of radionuclides between biota and surface waters and this interaction needs to be considered in a safety assessment for a repository at Forsmark.
   - Uptake by filter feeders can potentially affect chemical parameters such as pH and concentrations of oxygen and carbon dioxide which are important for transport and accumulation of radionuclides and this interaction needs to be considered in a safety assessment for a repository at Forsmark.

8:5 Filter feeders affect **gas and local atmosphere** in aquatic ecosystems by the processes a) Excretion, and b) Uptake.

a) Excretion – Filter feeders may excrete gases and thereby influence the gas fraction in water and regolith. However, considering the low amounts of filter feeders in the aquatic habitats of Forsmark, the gas excretion should be minor compared with e.g. that from decomposers. Therefore, this interaction should have only a minor effect on transport and accumulation of radionuclides and does not need to be considered in a safety assessment for a repository at Forsmark.

b) Uptake – Elements present in gas bubbles in water may be taken up by filter feeders. However, the uptake from gas bubbles should be minor compared with uptake from water and this process therefore does not need to be considered in a safety assessment for a repository at Forsmark.

8:6 Filter feeders affect **primary producers** in aquatic ecosystems by the processes a) Consumption, b) Habitat supply, and c) Stimulation/inhibition.

a) Consumption – Filter feeders may consume large quantities of primary producers (e.g. bivalves filtering phytoplankton). This may be important for the transport of radionuclides and needs to be considered in a safety assessment for a repository at Forsmark.

b) Habitat supply – Filter feeders may provide a substrate for epiphytic algae. This interaction does not significantly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in a safety assessment for a repository at Forsmark.

c) Stimulation/inhibition – Filter feeders may inhibit primary producers by e.g. competition for space. This interaction does not directly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in a safety assessment for a repository at Forsmark.

8:7 Filter feeders affect **decomposers** in aquatic ecosystems by the processes a) Consumption, b) Habitat supply, and c) Stimulation/inhibition.

a) Consumption – Filter feeders may consume large quantities of decomposers (e.g. bivalves filtering pelagic bacteria). This may be important for the transport of radionuclides and needs to be considered in a safety assessment for a repository at Forsmark.

b) Habitat supply – Filter feeders may provide a substrate for epiphytic bacteria. This interaction does not directly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in a safety assessment for a repository at Forsmark.

c) Stimulation/inhibition – Filter feeders may inhibit decomposers by e.g. competition for resources and substrate. This interaction does not significantly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in a safety assessment for a repository at Forsmark.

8:8 Filter feeders is a diagonal element as further described in Chapter 4. Filter feeders is internally affected by the features Geometry, Material composition, Stage of succession, Temperature, Water composition and Radionuclide inventory. Filter feeders affect filter feeders by the processes a) Consumption, b) Exposure, c) Food supply, d) Growth, e) Radioactive decay, and f) Stimulation/inhibition.

a) Consumption – Larval filter feeders may be consumed by other filter feeders. However, the consumption of filter feeders is small compared with the consumption of other organisms and particles. Therefore, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

b) Exposure – Exposure can either be external due to sources outside the body or internal due to sources inside the body. Concentration, location and type of radionuclides in surface waters, regolith, and in the atmosphere, i.e. in all parts of the biosphere system, affect the external exposure of, and the radiologic and toxic effects on, biota. Concentrations within biota affect the internal dose. The effects on organisms may include cellular death and affect biomass of filter feeders, and this interaction needs to be considered in a safety assessment for a repository at Forsmark.

c) Food supply – Filter feeders are available as a food source for other filter feeders as they may consume each other's larval stages. However, the consumption of filter feeders is small compared with the consumption of other organisms and particles. Therefore this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

d) Growth – Growth can potentially lower the concentration of radionuclides in biota due to dilution in biomass and needs to be considered in a safety assessment for a repository at Forsmark.

e) Radioactive decay – Radionuclides in the different biosphere components undergo radioactive decay where they transform into other radionuclides or form stable isotopes. Decay of radionuclides is important to consider in estimating the amounts of different radionuclides in the biosphere and this process needs to be considered in a safety assessment for a repository at Forsmark.

f) Stimulation/inhibition – Filter feeders may stimulate each other e.g. by mating. Filter feeders may inhibit each other by e.g. competition for resources. This interaction does not directly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in a safety assessment for a repository at Forsmark.

8:9 Filter feeders affect **herbivores** in aquatic ecosystems by the processes a) Consumption, and b) Stimulation/inhibition.

a) Consumption – Most herbivores are too large to be consumed by filter feeders (with the exception of some zooplankton) and filter feeders consumption of herbivores is assumed to be of minor importance for the transport of radionuclides. Thus, this interaction does not need to be considered in in a safety assessment for a repository at Forsmark.

b) Stimulation/inhibition – Filter feeders may indirectly stimulate herbivores by e.g. by feeding on other organisms competing with herbivores for resources. Filter feeders may inhibit herbivores, e.g. by competition for substrate. This interaction does not directly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in a safety assessment for a repository at Forsmark.

8:10 Filter feeders affect **carnivores** in aquatic ecosystems by the processes a) Consumption, b) Food supply, and c) Stimulation/inhibition.

a) Consumption – Carnivores (except for some larvae) are most likely too large to be consumed by filter feeders and this interaction is probably of minor importance for radionuclide transport. Thus, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

b) Food supply – Filter feeders may function as a food source for carnivores. This may be important for the transport of radionuclides and needs to be considered in a safety assessment for a repository at Forsmark.

c) Stimulation/inhibition – Filter feeders stimulate carnivores mainly indirectly by e.g. decreasing the amount of suspended particles in water, hence increasing thr visibility in the water column which, in turn, is beneficial for a hunting predator. Filter feeders may inhibit carnivores by e.g. competition for substrate. This interaction does not directly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in in a safety assessment for a repository at Forsmark.

8:11 Filter feeders affect **humans** in aquatic ecosystems by the processes a) Food supply, b) Material supply, and c) Stimulation/inhibition.

a) Food supply – Filter feeders may function as a food source for humans and this interaction needs to be considered in a safety assessment for a repository at Forsmark.

b) Material supply – Humans may use the shells from filter feeders in e.g. handicraft or as nutritional supplements in breeding of domestic birds. However, no activities of this kind in present-day Forsmark are known to the authors, and, even if they were, it would most likely contribute only to a minor degree to exposure, since the use of such material would most likely only be occasional. Therefore, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

c) Stimulation/inhibition – Some species of filter feeders, e.g. *Dreissena polymorpha*, are known to cause problems for human utilisation of water resources by e.g. clogging of water filters (Griffiths et al. 1991). However, the same species may improve water quality by grazing on toxic cyanobacteria and may be used as biofilters (Dionisio Pires et al. 2005). There are no species present in the aquatic ecosystems in Forsmark today that inhibit human utilisation and by cautious assuming that this will not occur in the future either, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

8:12 Filter feeders affect **external conditions** in aquatic ecosystems by the process a) Export.

a) Export – In a radionuclide perspective, export may be important for the ecosystem since the exporting biota may contain radionuclides and thereby there might be a dilution of radionuclides in the ecosystem. Because filter feeders are normally sessile, the main route of export could be through spawn which probably are quantitatively minor importance. In addition, although the export from a system may be important for the exporting system, the effect on the receiving ecosystem should, in contrast, in most cases be small (due to dilution in downstream aquatic objects). The export of filter feeders in Forsmark is regarded as quantitatively unimportant and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

9:1 Herbivores affect **geosphere** by the process a) Intrusion.

a) Intrusion – Herbivores normally penetrate at most a half metre through a regolith surface and it is highly unlikely that they would intrude to repository depths (> 30 m). Therefore, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

9:2 Herbivores affect **regolith** by the processes a) Bioturbation, b) Convection, c) Death, d) Excretion, e) Light-related processes, f) Reactions, g) Sorption/desorption, and h) Uptake.

a) Bioturbation – Herbivores may affect the regolith by bioturbation which may alter the physical properties and chemical composition of the upper regolith. Herbivores are assumed to have smaller effect through bioturbation than decomposers living in the regolith. Larger herbivores (e.g. cattle, rabbits etc) may dig into the regolith but have a local and limited direct effect on it. Therefore, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

b) Convection – Organisms can act as an insulator and thereby influence the temperature of the underlying regolith. However, the density of herbivores is small and the effect on the temperature will be insignificant. Thus, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

c) Death – Herbivores affect the amount of dead organic matter in the regolith mainly when dying. This flux may be important for the redistribution of radionuclides in the ecosystem and this interaction needs to be considered in a safety assessment for a repository at Forsmark.

d) Excretion – Herbivores in and on the regolith may excrete particles, radionuclides and other elements and compounds into the regolith.
    - The effect of the excretion of particles by herbivores on regolith in the ecosystems is minimal, since the excretion is very small compared with the volume of the regolith and does not need to be considered in a safety assessment for a repository at Forsmark.
    - Excretion of radionuclides by herbivores affects the concentrations of radionuclides in herbivores as well as in the regolith. The effect on the regolith is most probably small but due to the effect on herbivores themselves this interaction needs to be considered in a safety assessment for a repository at Forsmark.
    - Excretion of elements and compounds by herbivores affects chemical parameters such as pH and concentrations of oxygen and carbon dioxide which are important for transport and accumulation of radionuclides. However, the effect on regolith composition by herbivore excretion is small compared with the effects from excretion by decomposers and primary producers and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

e) Light-related processes – The colour and structure of biota can affect the adsorption of radiation and thereby affect temperature. The radiation absorption by herbivores in ecosystems will be very small compared with the radiation absorption by other components, e.g. water bodies and regolith, and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

f) Reactions – Reactions within biota may be exo- or endothermic and influence temperature. However, the metabolic heat of herbivores is limited compared with the heat absorption by e.g. the water bodies. Reactions also include degradation of toxicants by herbivores and affect the type and concentrations of toxicants in the regolith. This may be important for toxicants but is of less importance for the transport and accumulation of radionuclides. Thus, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

g) Sorption/desorption – Sorption and desorption of radionuclides by biota is important for the transport and accumulation of radionuclides and therefore needs to be considered in a safety assessment for a repository at Forsmark.

h) Uptake – Herbivores living in or on the regolith take up regolith (unintentional when feeding), radionuclides and other elements from the regolith.
   - The effect of the uptake of water by herbivores on the amount of regolith in regolith is small, since the uptake of water is very small compared with the water volume. Thus, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.
   - Uptake of radionuclides from the regolith by biota may be important for the distribution of radionuclides between biota and regolith. The effect is most likely small on the regolith but is important for the radionuclide concentration in biota. Thus, this interaction needs to be considered in a safety assessment for a repository at Forsmark.
   - Uptake by herbivores affects chemical parameters such as pH and concentrations of oxygen and carbon dioxide which are important for transport and accumulation of radionuclides. However, the effects on regolith composition by herbivore uptake are small compared with the effects from uptake by decomposers and primary producers and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

9:3 H**erbivores** affect **water in the regolith** by the processes a) Convection, b) Excretion, c) Light-related processes, d) Reactions, e) Sorption/desorption, and f) Uptake.

a) Convection – Organisms can act as an insulator and thereby influence the temperature of the underlying water in the regolith. However, the density of herbivores is small and the effect on the temperature will be insignificant. Thus this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

b) Excretion – Herbivores in and on the regolith may excrete water, radionuclides and other elements and compunds into the regolith.
   - The effect of the excretion of water by herbivores on the amount of water in regolith in the ecosystems is minimal, since the excretion of water is very small compared with the water volume in the regolith and does not need to be considered in a safety assessment for a repository at Forsmark.
   - Excretion of radionuclides by herbivores affects the concentrations of radionuclides in herbivores as well as in water in the regolith and needs to be considered in a safety assessment for a repository at Forsmark.
   - Excretion of elements and compounds by herbivores affects chemical parameters such as pH and concentrations of oxygen and carbon dioxide which are important for transport and accumulation of radionuclides. However, the effect on water composition by herbivore excretion is small compared with the effects from excretion by decomposers and primary producers and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

c) Light-related processes – The colour and structure of biota can affect the adsorption of radiation and thereby affect temperature. The radiation absorption by herbivores in ecosystems will be very small compared with the radiation absorption by the other components, e.g. water bodies and regolith, and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

d) Reactions — Reactions within biota may be exo- or endothermic and influence temperature. However, the metabolic heat of decomposers is limited compared with the heat absorption by e.g. the water bodies. Reactions also include degradation of toxicants by herbivores and affect the type and concentrations of toxicants in water in regolith. This may be important for toxicants but is of less importance for transport and accumulation of radionuclides. Thus, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

e) Sorption/desorption – Sorption and desorption of radionuclides by biota is important for the transport and accumulation of radionuclides and therefore needs to be considered in a safety assessment for a repository at Forsmark.

f) Uptake – Herbivores living in or on the regolith take up water, radionuclides and other elements from the regolith.

- The effect of the uptake of water by herbivores on the amount of water in regolith is small, since the uptake of water is very small compared with the water volume. Thus, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.
- Uptake of radionuclides from water in the regolith by biota may be important for the distribution of radionuclides between biota and regolith. Thus, this interaction needs to be considered in a safety assessment for a repository at Forsmark.
- Uptake by herbivores affects chemical parameters such as pH and concentrations of oxygen and carbon dioxide which are important for transport and accumulation of radionuclides. However, the effects on water composition by herbivore uptake are small compared with the effects from uptake by decomposers and primary producers and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

9:4 Herbivores affect **surface waters** by the processes a) Acceleration, b) Death, c) Excretion, d) Light-related processes, e) Movement, f) Particle Release/trapping, g) Reactions, h) Sorption/desorption, and i) Uptake.

a) Acceleration – The type and amount of herbivores attached to surfaces (e.g. snails) may hypothetically influence the properties of the surfaces and thereby water movement in aquatic ecosystems. However, other forcing factors will have greater effects on surface water movement than herbivores. In terrestrial ecosystems no known interaction of this kind is identified and this interaction therefore does not need to be considered in a safety assessment for a repository at Forsmark.

b) Death – Herbivores affect the amount of dead organic matter in water mainly when dying. This flux may be important for the redistribution of radionuclides in the ecosystem and therefore needs to be considered in a safety assessment for a repository at Forsmark.

c) Excretion – Herbivores may excrete water, radionuclides and other elements and compunds into the surface water.
   - The excretion of water by herbivores is very small compared with the water volume of the aquatic system and to surface waters in terrestrial ecosystems, and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.
   - Excretion of radionuclides by herbivores affects the concentration of radionuclides in herbivores as well as in surface waters and needs to be considered in a safety assessment for a repository at Forsmark.
   - Excretion of elements and compounds by herbivores affects chemical parameters such as pH and concentrations of oxygen and carbon dioxide which are important for transport and accumulation of radionuclides. However, the effect on water composition by herbivore excretion is small compared with the effects from excretion by decomposers and primary producers and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

d) Light-related processes – The colour and structure of biota can affect the adsorption of radiation and thereby affect temperature. The radiation absorption by herbivores in ecosystems will be very small compared with the radiation absorption by other components, e.g. water bodies and regolith, and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

e) Movement – The movement of large herbivores in surface waters may have an influence on surface water movement. However, the animals will most probably not affect large water bodies such as lakes and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

f) Particle release/trapping – The amount of particles in water is important for the transport of radionuclides attached to particle surfaces. Particle release by herbivores in aquatic ecosystems may sometimes be intense (e.g. at spawning) but most often the contribution to particle release and trapping from herbivores is assumed to be small. In terrestrial ecosystems the release and trapping of particles to/from surface water by herbivores is assumed to be insignificant. Therefore, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

g) Reactions – Reactions within biota may be exo- or endothermic and influence temperature. However, the metabolic heat of herbivores is limited compared with the heat absorption by e.g.

the water bodies. Reactions also include degradation of toxicants by herbivores and affect the type and concentrations of toxicants in surface waters. This may be important for toxicants but is of less importance for transport and accumulation of radionuclides. Thus, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

h) Sorption/desorption – Sorption and desorption of radionuclides by biota is important for the transport and accumulation of radionuclides and therefore needs to be considered in a safety assessment for a repository at Forsmark.

i) Uptake – Herbivores may take up water, radionuclides and other elements from surface waters.
   - The uptake of water by herbivores is very small compared with the water volume of the aquatic system and to surface waters in terrestrial ecosystems in Forsmark, and this interaction therefore does not need to be considered in a safety assessment for a repository at Forsmark.
   - Uptake of radionuclides from surface waters by biota may be important for the distribution of radionuclides between biota and surface waters. Thus, this interaction needs to be considered in a safety assessment for a repository at Forsmark.
   - Uptake by herbivores affects chemical parameters such as pH and concentrations of oxygen and carbon dioxide which are important for transport and accumulation of radionuclides. However, the effect on water composition by herbivore uptake is small compared with the effects from uptake by decomposers and primary producers and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

9:5 Herbivores affect **gas and local atmosphere** by the processes a) Excretion, b) Light-related processes, c) Particle release/trapping, d) Reactions, e) Sorption/desorption, and f) Uptake.

a) Excretion – Herbivores excrete radionuclides and other elements to the atmosphere and gas phase of water.
   - Excretion of radionuclides by herbivores affects the concentration of radionuclides in those herbivores, as well as in the atmosphere, and needs to be considered in a safety assessment for a repository at Forsmark.
   - Herbivores (e.g. herbivorous zooplankton in aquatic ecosystems and grazing animals in terrestrial ecosystems) may excrete gases and thereby influence the gas fraction in water, regolith and local atmosphere. However, the gas excretion should be small from herbivores and have little effect on gas and local atmosphere. Therefore, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

b) Light-related processes – The colour and structure of biota can affect the adsorption of radiation and thereby affect temperature. The radiation absorption by herbivores in ecosystems will be very small compared with the radiation absorption by other components, e.g. water bodies and regolith, and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

c) Particle release/trapping – Herbivorous birds may release or trap particles in the atmosphere. However, this interaction is assumed to be minimal in comparison with the particle release and trapping by e.g. primary producers and this interaction does not need to be considered in the safety assessment for a repository at Forsmark.

d) Reactions – Reactions within biota may be exo- or endothermic and influence temperature. However, the metabolic heat of herbivores is limited compared with the heat absorption by e.g. the water bodies and therefore this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

e) Sorption/desorption – Sorption and desorption of radionuclides by biota is important for the transport and accumulation of radionuclides and therefore needs to be considered in a safety assessment for a repository at Forsmark. The abundance of herbivores is not so large that large effects on the concentrations in the atmosphere are expected. Nevertheless, since sorption/desorption may have a large effect on biota this interaction is still recommended to be included.

f) Uptake – Herbivores take up radionuclides and elements from the atmosphere and gas phase.
   - Uptake of radionuclides from the atmosphere by biota may be important for the distribution of radionuclides between biota and atmosphere. Thus, this interaction needs to be considered in a safety assessment for a repository at Forsmark.

- Herbivores take up mainly oxygen from the atmosphere and gas phase of water. In terrestrial ecosystems, uptake of elements by herbivores should have minor effect on the gas and local atmosphere. In aquatic ecosystems, uptake of oxygen may cause oxygen deficit, especially during stratified conditions in winter. However, uptake by herbivores is small compared with the oxygen uptake by decomposers and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

9:6 Herbivores affect **primary producers** by the processes a) Consumption, and b) Stimulation/inhibition.

a) Consumption – Consumption of primary producers is an important transfer of energy in the ecosystem and this interaction is important to consider in a safety assessment for a repository at Forsmark.

b) Stimulation/inhibition – Herbivores may inhibit some species of primary producers by e.g. substrate competition. Besides that, herbivores mainly indirectly stimulate primary producers by inhibiting other organisms, e.g. changed competition. This interaction does not directly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered a safety assessment for a repository at Forsmark.

9:7 Herbivores affect **decomposers** by the process a) Stimulation/inhibition.

a) Stimulation/inhibition – Herbivores may stimulate decomposers by e.g. differences in the quality of food produced. Herbivores may inhibit decomposers by e.g. substrate competition. This interaction does not directly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in a safety assessment for a repository at Forsmark.

9:8 Herbivores affect **filter feeders** in aquatic ecosystems by the processes a) Food supply, and b) Stimulation/inhibition.

a) Food supply – Herbivores may provide a food source for filter feeders (e.g. zooplankton and gametes). However, most herbivores are too large to be consumed by filter feeders and this interaction is probably of minor importance for the transport of radionuclides. Thus, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

b) Stimulation/inhibition – Herbivores stimulate filter feeders by e.g. providing food of different quality. Herbivores may inhibit filter feeders by e.g. competition for substrate and resources. This interaction does not directly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in a safety assessment for a repository at Forsmark.

9:9 Herbivores are a diagonal element as further described in Chapter 4. Herbivores is internally affected by the features Geometry, Material composition, Stage of succession, Temperature, Water composition and Radionuclide inventory. Herbivores affect herbivores by the processes a) Exposure, b) Growth, c) Radioactive decay, and d) Stimulation/inhibition.

a) Exposure – Exposure can either be external due to sources outside the body or internal due to sources inside the body. Concentration, location and type of radionuclides in surface waters, regolith, and in the atmosphere, i.e. in all parts of the biosphere system, affect the external exposure of, and the radiologic and toxic effects on, biota. Concentrations within biota affect the internal dose. The effects onorganisms may include cellular death and affect biomass of herbivores, and this interaction needs to be considered in a safety assessment for a repository at Forsmark.

b) Growth – Growth can potentially lower the concentration of radionuclides in biota due to dilution in biomass and needs to be considered in a safety assessment for a repository at Forsmark.

c) Radioactive decay – Radionuclides in the different biosphere components undergo radioactive decay where they transform into other radionuclides or form stable isotopes. Decay of radionuclides is important to consider in estimating the amounts of different radionuclides in the biosphere and this process needs to be considered in a safety assessment for a repository at Forsmark.

d) Stimulation/inhibition – Herbivores may inhibit each other by e.g. competition for substrate and resources. Herbivores may stimulate each other by e.g. mating. This interaction does not directly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in a safety assessment for a repository at Forsmark.

9:10 Herbivores affect **carnivores** by the processes a) Food supply, and b) Stimulation/inhibition.

a) Food supply – Herbivores may function as a food source for carnivores. This may be an important pathway for radionuclide transfer and needs to be considered in a safety assessment for a repository at Forsmark.

b) Stimulation/inhibition – Herbivores may stimulate carnivores by e.g. providing food of different quality and may inhibit carnivores by e.g. substrate competition. Usually herbivores are not assumed to compete with carnivores for substrate but omnivores which is a mix of herbivores and carniovores compete for substrate. This interaction does not directly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in a safety assessment for a repository at Forsmark.

9:11 Herbivores affect **humans** by the processes a) Food supply, b) Material supply, and c) Stimulation/inhibition.

a) Food supply – Herbivores may function as a food source for humans who may consume herbivorous fish, domesticated animals or game. This interaction may be an important radionuclide transport route to humans and is important to include in a safety assessment for a repository at Forsmark.

b) Material supply – From terrestrial ecosystems, skins from herbivores may be used for clothing. Also from aquatic ecosystems, it occur that shoes and various accessories are manufactured from for example from fish skin (Rahme and Hartman 2006). The external exposure from this pathway is most likely very small compared to living in a contaminated area and does not need to be considered in a safety assessment for a repository at Forsmark.

c) Stimulation/inhibition – There is no identified stimulation or inhibition by herbivores of human utilisation of the ecosystem at Forsmark except for fishing or hunting which is treated in food supply (see a, above). Therefore, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

9:12 Herbivores affect **external conditions** by the process a) Export.

a) Export – In a radionuclide perspective, export may be important for the ecosystem radionuclide inventory if contaminated biota migrate, since it could cause a dilution of radionuclides in the ecosystem. The effect on the receiving ecosystem should, in contrast, in most cases be small (due to dilution in downstream aquatic objects). The export of herbivores in Forsmark is assumed to be of small quantity and does not need to be considered in a safety assessment for a repository at Forsmark.

10:1 Carnivores affect **geosphere** by the process a) Intrusion.

a) Intrusion – Carnivores normally penetrate at most a half a metre through a regolith surface and it is highly unlikely that they would intrude to depths of a repository (> 30 m). Therefore, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

10:2 Carnivores affect **regolith** by the process a) Bioturbation, b) Convection, c) Death, d) Excretion e) Light-related processes, f) Reactions, g) Sorption/desorption and h) Uptake.

a) Bioturbation – Carnivores may affect the regolith by bioturbation which may alter physical properties and chemical composition of the upper regolith. However, carnivores most probably have a local and limited effect on the regolith and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

b) Convection – Organisms can act as an insulator between atmosphere and underlying water and regolith thereby affecting the transport of heat in the biosphere. However, the density of carnivores is small and other factors will have greater impact on temperature in the ecosystems. Thus this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

c) Death – Carnivores affect the amount of dead organic matter in the regolith mainly when dying. This flux may be important for the redistribution of radionuclides in the ecosystem. However, in practice, this flux is likely to be much lower than that associated with herbivores and primary producers and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

d) Excretion – Carnivores in and on the regolith may excrete particles, radionuclides and other elements and compounds into the regolith.
   - The effect of the excretion of particles by carnivores on regolith in the ecosystems is minimal, since the excretion is very small compared with the volume of the regolith and does not need to be considered in a safety assessment for a repository at Forsmark.
   - Excretion of radionuclides by carnivores affects the concentrations of radionuclides in carnivores as well as in regolith. The effect on the regolith is most probably small but due to the effect on carnivores themselves this interaction needs to be considered in a safety assessment for a repository at Forsmark.
   - Excretion of elements and compounds by carnivores affects chemical parameters such as pH and concentrations of oxygen and carbon dioxide which are important for transport and accumulation of radionuclides. However, the effect on regolith composition by carnivore excretion is small compared with the effects from excretion by decomposers and primary producers and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

e) Light-related processes – The colour and structure of biota can affect the adsorption of radiation and thereby affect temperature. The radiation absorption by carnivores in ecosystems will be very small compared with the radiation absorption by the other components, e.g. water bodies and regolith, and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

f) Reactions – Reactions within biota may be exo- or endothermic and influence temperature. However, the metabolic heat of carnivores is limited compared with the heat absorption by e.g. the water bodies. Reactions also include degradation of toxicants by carnivores and affect the type and concentrations of toxicants in the regolith. This may be important for toxicants, but are of less importance for transport and accumulation of radionuclides. Thus, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

g) Sorption/desorption – Sorption and desorption of radionuclides by biota is important for the transport and accumulation of radionuclides. However, the density of carnivores is low compared to e.g. primary producers and decomposers and thus this interaction is not important to consider for the concentrations of radionuclides in the regolith but the process is important to consider for the exposure of carnivores (interaction 2:10) therefore needs to be considered in a safety assessment for a repository at Forsmark.

h) Uptake – Carnivores living in or on the regolith take up regolith (unintentional when feeding), radionuclides and other elements from the regolith.
   - Uptake of radionuclides from the regolith by biota may be important for the distribution of radionuclides between biota and regolith. The effect is most likely small on the regolith but is important for the radionuclide concentration in biota. Thus, this interaction needs to be considered in a safety assessment for a repository at Forsmark.
   - Uptake by carnivores affects chemical parameters such as pH and concentrations of oxygen and carbon dioxide which are important for transport and accumulation of radionuclides. However, the effects on regolith composition by carnivore uptake are small compared with the effects from uptake by decomposers and primary producers and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

10:3 Carnivores affect **water in regolith** by the processes a) Convection, b) Excretion, c) Light-related processes, d) Reactions, e) Sorption/desorption, and f) Uptake.

a) Convection – Organisms can act as an insulator between atmosphere and underlying water and regolith thereby affecting the transport of heat in the biosphere. However, the density of carnivores is small and other factors will have greater impact on temperature in the ecosystems. Thus, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

b) Excretion – Carnivores in and on the regolith may excrete water, radionuclides and other elements and compounds into the water in regolith.
   - The effect of the excretion of water by carnivores on the amount of water in regolith in the ecosystems is minimal, since the excretion of water is very small compared to the water volume in the regolith and does not need to be considered in a safety assessment for a repository at Forsmark.
   - Excretion of radionuclides by carnivores affects the concentration of radionuclides in carnivores as well as in water in the regolith and needs to be considered in a safety assessment for a repository at Forsmark.
   - Excretion of elements and compounds by carnivores affects chemical parameters such as pH and concentrations of oxygen and carbon dioxide which are important for transport and accumulation of radionuclides. However, the effect on water composition by carnivore excretion is small compared with the effects from excretion by decomposers and primary producers and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

c) Light-related processes – The colour and structure of biota can affect the adsorption of radiation and thereby affect temperature. The radiation absorption by carnivores in ecosystems will be very small compared to the radiation absorption by other components, e.g. water bodies and regolith, and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

d) Reactions – Reactions within biota may be exo- or endothermic and influence temperature. However, the metabolic heat of carnivores is limited compared with the heat absorption by e.g. the water bodies. Reactions also include degradation of toxicants by carnivores and affect the type and concentrations of toxicants in water in the regolith. This may be important for toxicants but is of less importance for transport and accumulation of radionuclides. Thus, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

e) Sorption/desorption – Sorption and desorption of radionuclides by biota is important for the transport and accumulation of radionuclides and therefore needs to be considered in a safety assessment for a repository at Forsmark.

f) Uptake – Carnivores living in or on the regolith take up water, radionuclides and other elements from the water in the regolith. Terrestrial carnivores mostly take up water from surface waters but there are aquatic carnivores living in sediment which take up water from regolith.
   - The effect of the uptake of water by carnivores on the amount of water in the regolith is small, since the uptake of water is very small compared with the water volume. Thus, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.
   - Uptake of radionuclides from water in the regolith by carnivores may be important for the distribution of radionuclides between biota and regolith. The effect is most likely small on the regolith but is important for the radionuclide concentration in biota. Thus, this interaction needs to be considered in a safety assessment for a repository at Forsmark.
   - Uptake by carnivores affects chemical parameters such as pH and concentrations of oxygen and carbon dioxide which is important for transport and accumulation of radionuclides. However, the effect on water composition by carnivore uptake is small compared to the effects from uptake by decomposers and primary producers and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

10:4 Carnivores affect **surface waters** by the processes a) Death, b) Excretion, c) Light-related processes, d) Movement, e) Particle release/trapping, f) Reactions, g) Sorption/desorption, and h) Uptake.

a) Death – Carnivores affect the amount of dead organic matter in water mainly when dying. This flux may be important for the redistribution of radionuclides in the ecosystem. However, in practice, this flux is likely to be much lower than that associated with herbivores and primary producers and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

b) Excretion – Carnivores may excrete water, radionuclides and other elements and compounds into surface waters.
   - The excretion of water by carnivores is very small compared with the water volume of the aquatic system and the surface water in terrestrial ecosystems, and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.
   - Excretion of radionuclides by carnivores affects the concentration of radionuclides in carnivores as well as in surface water and needs to be considered in a safety assessment for a repository at Forsmark.
   - Excretion of elements and compounds by carnivores affects chemical parameters such as pH and concentrations of oxygen and carbon dioxide which are important for transport and accumulation of radionuclides. However, the effect on water composition by carnivore excretion is small compared with the effects from excretion by decomposers and primary producers and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

c) Light-related processes – The colour and structure of biota can affect the absorption of radiation and thereby affect temperature. The radiation absorption by carnivores in ecosystems will be very small compared with the radiation absorption by other components, e.g. water bodies and regolith, and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

d) Movement – The movement of carnivores in surface waters may have an influence on surface-water movement. However, the movement of animals is assumed to have small effect compared with other forcing factors such as wind. Thus, this interaction does not need to be considered.

e) Particle release/trapping – The concentration of particles in water is important for the transport of radionuclides attached to particle surfaces. Particle release by aquatic carnivores may sometimes be intense (e.g. at spawning) but most often the contribution to particle release and trapping from carnivores is assumed to be small. In terrestrial ecosystems the release and trapping of particles to/from surface waters by carnivores is assumed to be insignificant. Therefore, this interaction does not need to be considered in safety assessment for a repository at Forsmark.

f) Reactions – Reactions within biota may be exo- or endothermic and influence temperature. However, the metabolic heat of carnivores is limited compared with the heat absorption by e.g. the water bodies. Reactions also include degradation of toxicants by carnivores and affect the type and concentration of toxicants in surface waters. This may be important for toxicants but is of less importance for transport and accumulation of radionuclides. Thus, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

g) Sorption/desorption – Sorption and desorption of radionuclides by biota is important for the transport and accumulation of radionuclides and therefore need to be considered in a safety assessment for a repository at Forsmark.

h) Uptake – Carnivores may take up water, radionuclides and other elements from surface waters.
   - The uptake of water by carnivores is very small compared with the water volume of the aquatic system and the terrestrial surface waters and this interaction therefore does not need to be considered in a safety assessment for a repository at Forsmark.
   - Uptake of radionuclides from surface waters by biota may be important for the distribution of radionuclides between biota and surface waters. Thus, this interaction needs to be considered in a safety assessment for a repository at Forsmark.
   - Uptake by carnivores affects chemical parameters such as pH and concentrations of oxygen and carbon dioxide which are important for transport and accumulation of radionuclides. However, the effect on water composition by carnivore uptake is small compared with the effects from uptake by decomposers and primary producers and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

10:5 Carnivores affect **gas and local atmosphere** by the processes a) Excretion, b) Light-related processes, c) Particle release/trapping, d) Reactions, e) Sorption/desorption, and f) Uptake.

a) Excretion – Carnivores excrete radionuclides and other elements to the atmosphere and gas phase of water.
   - Excretion of radionuclides by carnivores affects the concentration of radionuclides in carnivores as well as in the atmosphere and needs to be considered in a safety assessment for a repository at Forsmark.

- Carnivores may excrete gases and thereby influence the gas fraction in water, regolith and local atmosphere. However, the gas excretion should be small from carnivores and will have little effect on gas and local atmosphere. Therefore, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

b) Light-related processes – The colour and structure of biota can affect the adsorption of radiation and thereby affect temperature. The radiation absorption by carnivores in ecosystems will be very small compared with the radiation absorption by other components, e.g. water bodies and regolith, and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

c) Particle release/trapping – Carnivorous birds may release or trap particles to/from the atmosphere but this interaction is assumed to be minimal in comparison with particle release trapping by e.g. primary producers and this interaction therefore does not need to be considered in a safety assessment for a repository at Forsmark.

d) Reactions – Reactions within biota may be exo- or endothermic and influence temperature. However, the metabolic heat of carnivores is limited compared with the heat absorption by e.g. the water bodies. Reactions also include degradation of toxicants by carnivores and affect the type and concentrations of toxicants in the atmosphere. This may be important for toxicants but is of less importance for transport and accumulation of radionuclides. Thus, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

e) Sorption/desorption – Sorption and desorption of radionuclides by biota is important for the transport and accumulation of radionuclides and therefore need to be considered in a safety assessment for a repository at Forsmark. The abundance of carnivores is not so large that large effects on the concentrations in the atmosphere are expected. Nevertheless, since sorption/desorption may have a large effect on biota this interaction is still recommended to be included.

f) Uptake – Carnivores take up radionuclides and other elements from the atmosphere and gas phase.
   - Uptake of radionuclides from atmosphere by biota may be important for the distribution of radionuclides between biota and atmosphere. Thus, this interaction needs to be considered in a safety assessment for a repository at Forsmark.
   - Carnivores take up mainly oxygen from the atmosphere and the gas phase of water. In terrestrial ecosystems, uptake of elements by carnivores should have minor effect on the gas and local atmosphere. In aquatic ecosystems, uptake of oxygen may cause oxygen deficit, especially during stratified conditions in winter. However, uptake by carnivores is small compared to the oxygen uptake by decomposers and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

10:6 Carnivores affect **primary producers** by the process a) Stimulation/inhibition.

a) Stimulation/inhibition – Carnivores mainly stimulate primary producers indirectly by reducing the amounts of herbivores, i.e. the main effect carnivores have on primary producers is via the interaction 10:9 below. The direct stimulation/inhibition of primary producers by carnivores is generally low and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

10:7 Carnivores affect **decomposers** by the processes a) Consumption, and b) Stimulation/inhibition.

a) Consumption – Carnivores consume decomposers. This may be important for the transport of radionuclides and needs to be considered in a safety assessment for a repository at Forsmark.

b) Stimulation/inhibition – Carnivores may stimulate decomposers by e.g. by providing food of different quality. Carnivores may inhibit decomposers by e.g. resource competition. This interaction does not directly influence the transport of radionuclides in the ecosystem and therefore does not need to be considered in a safety assessment for a repository at Forsmark.

10:8 Carnivores affect **filter feeders** in the aquatic ecosystems by the processes a) Consumption, b) Food supply, and c) Stimulation/inhibition.

a) Consumption – Carnivores consume filter feeders. This may be important for the transport of radionuclides and needs to be considered in a safety assessment for a repository at Forsmark.

b) Food supply – Carnivores may function as a food source for filter feeders. However, carnivores (except for some larvae) are most likely too large to be consumed by filter feeders and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

c) Stimulation/inhibition – Carnivores may inhibit filter feeders by e.g. resource competition. This interaction does not directly influence the transport and accumulation of radionuclides in the ecosystem and therefore does not need to be considered in a safety assessment for a repository at Forsmark.

10:9 Carnivores affect **herbivores** by the processes a) Consumption, and b) Stimulation/inhibition.

a) Consumption – Carnivores consume herbivores. This may be important for the transport of radionuclides and needs to be considered in a safety assessment for a repository at Forsmark.

b) Stimulation/inhibition – Carnivores may stimulate or inhibit some species of herbivores by favouring certain species in their diet. This interaction does not directly influence the transport of radionuclides in the ecosystem and therefore does not need to be considered in a safety assessment for a repository at Forsmark.

10:10 Carnivores are a diagonal element as further described in Chapter 4. Carnivores is internally affected by the features Geometry, Material composition, Stage of succession, Temperature, Water composition and Radionuclide inventory. Carnivores affect carnivores by the processes a) Consumption, b) Exposure, c) Food supply, d) Growth, e) Radioactive decay, and f) Stimulation/inhibition.

a) Consumption – Carnivores consume carnivores. This may be important for the transport of radionuclides and needs to be considered in a safety assessment for a repository at Forsmark.

b) Exposure – Exposure can either be external due to sources outside the body or internal due to sources inside the body. Concentration, location and type of radionuclides in surface waters, regolith, and in the atmosphere, i.e. in all parts of the biosphere system, affect the external exposure of, and the radiologic and toxic effects on, biota. Concentrations within biota affect the internal dose. The effects onorganisms may include cellular death and affect biomass of carnivores, and this interaction needs to be considered in a safety assessment for a repository at Forsmark.

c) Food supply – Carnivores may function as a food source for other carnivores. This may be important for transport and accumulation of radionuclides and needs to be considered in a safety assessment for a repository at Forsmark.

d) Growth – Growth can potentially lower the concentration of radionuclides in biota due to dilution in biomass and needs to be considered in a safety assessment for a repository at Forsmark.

e) Radioactive decay – Radionuclides in the different biosphere components undergo radioactive decay where they transform into other radionuclides or form stable isotopes. Decay of radionuclides is important to consider in estimating the amounts of different radionuclides in the biosphere and this process needs to be considered in a safety assessment for a repository at Forsmark.

f) Stimulation/inhibition – Carnivores may stimulate each other by e.g. mating. Carnivores may inhibit each other by e.g. competition for space and resources. This interaction does not directly influence the transport of radionuclides in the ecosystem and therefore does not need to be considered in a safety assessment for a repository at Forsmark.

10:11 Carnivores affect **humans** by the processes a) Consumption, b) Food supply, c) Material supply, and d) Stimulation/inhibition.

a) Consumption – In the ecosystems at Forsmark there are no carnivores that feed on humans at present. Even if carnivores that could kill and eat humans (e.g. bears) were to occupy Forsmark feeding on humans by carnivores would be assumed to occur at very low frequency and not to have a large effect on the transport and accumulation of radionuclides. Therefore, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

b) Food supply – Carnivores, e.g. mammals and carnivorous fish may function as a food source for humans. This can be an important route of transport of radionuclides to humans and needs to be considered in a safety assessment for a repository at Forsmark.

c) Material supply – From terrestrial ecosystems, skins from carnivores may be used for clothing. Also, from aquatic ecosystems, it occur that shoes and various accessories are manufactured from for example from fish skin (Rahme and Hartman 2006). The external exposure from this pathway is most likely very small compared with living in a contaminated area and does not need to be considered in a safety assessment for a repository at Forsmark.

d) Stimulation/inhibition – There is no identified stimulation or inhibition by carnivores of human utilisation of the ecosystems at Forsmark and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

10:12 Carnivores affect **external conditions** by the process a) Export.

b) Export – In a radionuclide perspective, export may be important for the ecosystem radionuclide inventory if contaminated biota migrate, since it could cause a dilution of radionuclides in the ecosystem. The effect on the receiving ecosystem should, in contrast, in most cases be small. The export of carnivores in Forsmark is assumed to be of small quantity and does not need to be considered in a safety assessment for a repository at Forsmark.

11:1 Humans affect **geosphere** by the processes a) Intrusion, and b) Material use.

a) Intrusion – Human intrusion may have a large impact on radionuclide transport and needs to be considered in a safety assessment for a repository at Forsmark.

b) Material use – Minerals and fossil fuels in the geosphere may be used by humans, as well as the rock itself for storage purposes (c.f. 1:11). Iron ores have been utilised in the Bergslagen region (Uppland), and are still utilised today in Dannemora (www.dannemoramineral.se). Compared with central parts of Bergslagen, the Forsmark area's ore potential is insignificant and the entire repository site is free of ore potential (Lindroos et al. 2004). These types of possible material use need to be discussed in a safety assessment but do not need to be considered in the biosphere part of a safety assessment for a repository at Forsmark.

11:2 Humans affect **regolith** by the processes a) Anthropogenic release, b) Consolidation, c) Consumption, d) Convection, e) Death, f) Excretion, g) Material use, h) Relocation, and i) Sorption/desorption.

a) Anthropogenic release – Humans may release heat, radionuclides and other elements into the regolith.
   - Anthropogenic release of heat from e.g. industries may lead to increased temperature and global warming. Global warming is important to consider in the assessment but is not part of the internal biosphere IM. Effects of heating on a local scale could be considered in supporting calculation cases, for example when evaluation future human actions.
   - Anthropogenic release of radionuclides can affect the concentration of radionuclides in the biosphere system by e.g. the operation of nuclear facilities or by use of contaminated material from one area in another. The release of radionuclides from nuclear facilities is beyond the scope of safety assessments and the interaction does not need to be considered in a safety assessment for a repository at Forsmark. However, if humans e.g. relocate radionuclides by fertilising with organic matter originating from an area with release from the repository, radionuclides could become concentrated in a smaller area. This may be important for the exposure and needs to be considered in a safety assessment for a repository at Forsmark.
   - Anthropogenic release of other substances than radionuclides may alter the material composition of the regolith. No large-scale releases of substances are expected assuming present behaviour of people and current legislation. However, such scenarios could be considered in supporting calculations if chemical conditions of the regolith are assumed to have an effect on the impacts of a repository at Forsmark.

b) Consolidation – If humans drain wetlands in order to gain farmland they will affect regolith which will be compacted. This may affect the concentrations of radionuclides in the regolith and are thus needs to be considered in a safety assessment for a repository at Forsmark.

c) Consumption – Consumption of radionuclides from the regolith by humans could occur accidently during food intake or by small children. Although inadvertent ingestion of soil normally contribute little to doses, it is suggested in interaction 2:11 that consumption is evaluated for a safety assessment. However, the importance for the characteristics of the regolith is very small and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

d) Convection – Humans may affect the flow of heat in the regolith by constructing e.g. houses that in turn affect temperature by isolation. However, in comparison with other factors in the ecosystems, this is assumed to be insignificant and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

e) Death – Humans may affect the amount of dead organic matter in regolith by e.g. municipal release. This flux should however be of minor importance for the transport and accumulation of radionuclides in the ecosystems and does not need to be considered in a safety assessment for a repository at Forsmark.

f) Excretion – Human excretion is assumed to have insignificant effect on the regolith and does not need to be considered in considered in a safety assessment for a repository at Forsmark.

g) Material use – Regolith may be utilised by humans, e.g. peat used as fuel, which may alter the regolith distribution in the biosphere. Although this is not currently occurring in Forsmark, it may affect the ecosystems and may be an exposure pathway for humans and needs to be considered in a safety assessment for a repository at Forsmark.

h) Relocation – Humans may affect and relocate regolith by e.g. dredging, digging and filling. Humans may lower thresholds in lakes (thereby affecting the regolith) to gain farmland. The transformation to farmland and thresholds may be important for the transport and accumulation of radionuclides and this interaction needs to be considered in a safety assessment for a repository at Forsmark.

i) Sorption/desorption – Sorption of radionuclides to humans either in terrestrial or aquatic ecosystems is assumed to have an insignificant effect on the radionuclide inventories in the ecosystem where they are sorbed. However, the sorption of radionuclides may have an effect on the exposure of humans, (2:11) which is important to consider. The effect on the radionuclide inventory in the biotic components on the other hand should be minimal and does not need to be considered in a safety assessment for a repository at Forsmark.

11:3 Humans affect **water in regolith** by the processes a) Anthropogenic release, b) Convection, c) Excretion, d) Uptake, and e) Water use.

a) Anthropogenic release – Humans may release heat, radionuclides and other elements into the water in the regolith.
   - Anthropogenic release of heat from e.g. industries may lead to increased temperature and global warming. Temperature changes leading to different climate conditions may have an effect on transport and accumulation of radionuclide. Global warming is important to consider in the assessment but is not part of the internal biosphere IM. Effects of heating on a local scale could be considered in supporting calculation case, for example when evaluation future human actions.
   - Anthropogenic release of radionuclides can affect the concentration of radionuclides in the biosphere system by e.g. the operation of nuclear facilities. The release of radionuclides from nuclear facilities is beyond the scope of safety assessments and the interaction does not need to be considered in a safety assessment for a repository at Forsmark. However, if humans e.g. relocate radionuclides by fertilising with organic matter originating from an area with release from the repository, radionuclides could become concentrated in a smaller area. This may be important for the exposure and needs to be considered in a safety assessment for a repository at Forsmark.
   - Anthropogenic release of other substances than radionuclides may alter the material composition of the water in the regolith. No large-scale releases of substances are expected assuming present behaviour of people and current legislation. However, such scenarios could be considered in supporting calculations since chemical conditions of regolith are assumed to have an effect on the impacts of a repository at Forsmark.

b) Convection – Humans may affect the flow of heat by constructing e.g. houses that in turn affect temperature by isolation. However, in comparison to other factors in the ecosystems, this is assumed to be insignificant and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

c) Excretion – Humans may excrete radionuclides and other elements. The excretion of radionuclides is important since it may affect the concentrations of radionuclides in the different biosphere compartments as well as affecting the exposure of humans. However, humans do not directly excrete elements to water in regolith but the interaction goes via anthropogenic release (above) or to surface waters and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

d) Uptake – Humans take up water from regolith by wells and thereby take up water, radionuclides and other elements present in groundwater.
   - Humans may affect the water content and flow in the regolith by extraction from wells for drinking. Intensive utilization may empty wells in dry summer months. This may affect the number of people living in an area and thus the transport of radionuclides to humans. Therefore, this interaction needs to be considered in a safety assessment for a repository at Forsmark.
   - Uptake of radionuclides from water in the regolith by humans may be important for the distribution of radionuclides between humans and water in the regolith. Thus, this interaction needs to be considered in a safety assessment for a repository at Forsmark.
   - Uptake of water by humans will not affect the composition of the remaining water in the regolith and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

e) Water use – Humans may affect the water content and flow in the regolith by e.g. water extraction from wells or artificial infiltration of municipal water. Intensive utilization may empty wells in dry summer months. This may affect the number of people living in an area and thus the transport of radionuclides to humans. Therefore, this interaction needs to be considered in a safety assessment for a repository at Forsmark.

11:4 Humans affect **surface water** by the processes a) Acceleration, b) Anthropogenic release, c) Covering, d) Death, e) Excretion, f) Movement g) Particle release/trapping, h) Sorption/desorption, i) Uptake, and j) Water use.

a) Acceleration – Humans may influence water movement by constructions, e.g. dams, large-scale export, piping, and wave generation. Dams may have effect on the retention time in aquatic systems although generally, humans are considered to have a small impact on water movement compared with natural forces. No human activities affecting large-scale water movements are expected assuming present behaviour of people and current legislation this interaction needs to be considered in a safety assessment for a repository at Forsmark.

b) Anthropogenic release – Humans may release heat, radionuclides, water and other elements into surface waters.
   - Anthropogenic release of heat from e.g. industries may lead to increased temperature and global warming. Temperature changes leading to different climate conditions may have an effect on transport and accumulation of radionuclide. Global warming is important to consider in the assessment but is not part of the internal biosphere IM. Effects of heating on a local scale could be considered in supporting calculation case, for example when evaluation future human actions.
   - Anthropogenic release of radionuclides can affect the concentration of radionuclides in the biosphere system by e.g. the operation of nuclear facilities. The release of radionuclides due to such activities is beyond the scope of safety assessments for a specific repository and the interaction does not need to be considered in a safety assessment for a repository at Forsmark.
   - Anthropogenic release of substances other than radionuclides may alter the material composition of the regolith. No large-scale releases of substances are expected assuming present behaviour of people and current legislation. However, such scenarios could be considered in supporting calculations if chemical conditions of surface waters are assumed to have an effect on the impacts of a repository at Forsmark.

c) Covering – Use of icebreakers by humans influences the amount of surfaces covered with ice and may thereby potentially influence surface water movement. The influence of icebreakers on surface water is considered insignificant and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

d) Death – Humans may affect the amount of dead organic matter in water by municipal release, which contains organic matter such as faeces. This flux should be minor compared with the dead organic matter produced by aquatic organisms and the effect on transport and accumulation of radionuclides should be insignificant. Therefore, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

e) Excretion – Humans may excrete water (urine), radionuclides and other elements and compounds.
   - Excretion of water by humans (urine) will not affect the amount of surface water in ecosystems since the volume is much smaller than the volume of surface waters and this interaction therefore does not need to be considered in a safety assessment for a repository at Forsmark.
   - Excretion of radionuclides by humans affects the concentration of radionuclides in humans but should have minor effect on the amounts in surface water due to the small amounts and large water volumes. Thus, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.
   - Humans may influence the water composition by sewage which is known to increase e.g. nitrogen and phosphorus concentrations in water. Although the effect should be small for the entire aquatic area there may be local effects on the water chemistry by sewage. However, the water exchange is rather rapid in the aquatic ecosystems in Forsmark (present and future) and therefore the excretion of humans is assumed to have a limited effect on the water composition and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

f) Movement – Like other animals, the movement of humans (e.g. swimming) could theoretically have an influence on the surface water movement. However, this is assumed to have insignificant effect on surface water movement compared with other forcing factors in nature. Humans are more likely to have an influence on water fluxes by other activities e.g. large scale export, piping, wave generation. Such activities and constructions are treated in the process 'acceleration' above and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

g) Particle release/trapping – Humans may affect the composition of surface waters by filtering e.g. drinking water. This will probably reduce any contaminants in the drinking water, but the effects on the surface water bodies are assumed to be negligible and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

h) Sorption/desorption – Sorption of radionuclides to humans either in terrestrial or aquatic ecosystems is assumed to have an insignificant effect on the radionuclide inventories in the ecosystem where they are sorbed. However, the sorption of radionuclides may have an effect on the exposure of humans (interaction 2:11) which it is important to consider. The effect on the radionuclide inventory in the biotic components on the other hand should be minimal and does not need to be considered in a safety assessment for a repository at Forsmark.

i) Uptake – Humans utilise surface waters and thereby take up water, radionuclides and other elements that are present.
   - Human uptake of surface water is relatively small compared with the volume of surface water and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.
   - Uptake of radionuclides from surface waters by humans may be important for the distribution of radionuclides between humans and surface water. Thus, this interaction needs to be considered in a safety assessment for a repository at Forsmark.
   - Humans may affect the water composition by filtering prior to using the water resource for drinking. Today, there is no large uptake by humans and most likely uptake will be small also in the future. If assuming prevailing conditions, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

j) Water use – Humans utilising lakes as a freshwater reservoir may influence the water levels. This may be important for the distribution of radionuclides and the interaction therefore needs to be considered in a safety assessment for a repository at Forsmark. Humans may also affect the water composition by filtering water before pumping. Filtering of water is assumed not to apply to a large quantity and therefore will have a limited impact on water composition and does not need to be considered in a safety assessment for a repository at Forsmark.

11:5 Humans affect **gas and local atmosphere** by the processes a) Acceleration, b) Anthropogenic release, c) Convection, d) Excretion, e) Light-related processes, f) Reactions, g) Sorption/desorption, and h) Uptake.

a) Acceleration – Humans can potentially influence wind velocities and wind fields by man-made structures such as buildings. This influence can be substantial in the immediate vicinity of those structures, whereas it is limited on a large scale. Therefore, the influence on mass transport is regarded as insignificant compared with natural causes for wind and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

b) Anthropogenic release. Humans may influence the radionuclide inventory, temperature and composition of the atmosphere by release from industries.
   - Global warming due to human release may affect transport and accumulation of radionuclides and therefore Temperature changes leading to different climate conditions may have an effect on transport and accumulation of radionuclide. However, global warming is important to consider in the assessment but is not part of the internal biosphere IM. Effects of heating on a local scale could be considered in supporting calculation case, for example when evaluation future human actions.
   - Human activities can affect the concentration of radionuclides in the biosphere system by e.g. the operation of nuclear facilities. The release of radionuclides due to such activities is beyond the scope of this safety analysis and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

c) Convection – Humans may affect the flow of heat by constructing e.g. houses that in turn affect temperature by isolation. For some radionuclides, the air exchange is important, and concentrations may differ between indoor and outdoor. Thus, this interaction needs to be considered in a safety assessment for a repository at Forsmark.

d) Excretion – Humans may excrete radionuclides and other substances to the atmosphere.
   - The excretion of radionuclides from humans may be important for humans but is assumed to have very limited effect on the atmosphere due to the small amount of excretion in relation to the large volume of the atmosphere. Thus, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.
   - Humans can by respiration and metabolism take up oxygen and release carbon dioxide. This is assumed to already be included in the composition of the atmosphere, i.e. even if the number of humans in an area increases they will have a limited effect on the composition of the atmosphere. Thus, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

e) Light-related processes – Human constructions may affect the radiation balance. However, the effect of human constructions on temperature is assumed to be small and therefore this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

f) Reactions – Reactions within humans give rise to metabolic heat, but this has a negligible effect on the temperature compared with other sources and does not need to be considered in a safety assessment for a repository at Forsmark.

g) Sorption/desorption – Sorption of radionuclides to humans either in terrestrial or aquatic ecosystems is assumed to have an insignificant effect on the radionuclide inventories in the ecosystem where they are sorbed. However, the sorption of radionuclides may have an effect on the exposure of humans (interaction 2:11) which it is important to consider. The effect on the radionuclide inventory in the biotic components on the other hand should be minimal and does not need to be considered in a safety assessment for a repository at Forsmark.

h) Uptake – Humans take up radionuclides and other elements from the atmosphere.
   - Uptake of radionuclides from the atmosphere by humans may be important for the distribution of radionuclides between humans and the atmosphere. Thus, this interaction needs to be considered in a safety assessment for a repository at Forsmark.
   - Uptake – Humans can by respiration and metabolism take up oxygen and release carbon dioxide. This is assumed to already be included in the composition of the atmosphere, i.e. even if the number of humans in an area increases they will have a limited effect on the composition of the atmosphere. Thus, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

11:6 Humans affect **primary producers** by the processes a) Consumption, b) Material use, c) Species introduction/extermination, and d) Stimulation/inhibition.

a) Consumption – Humans may potentially utilize primary producers as a food source. This may be important for humans (interaction 6:11) but may also affect primary producers by e.g. choice of crop type and yield and needs to be considered in a safety assessment for a repository at Forsmark.

b) Material use – Humans may utilise primary producers as building material etc. From terrestrial ecosystems, wood may be used in construction and reed belts may be used as in thatching. There are no aquatic primary producers in the ecosystems in Forsmark today that are being utilized. Forestry may affect the vegetation pattern but by assuming present conditions, the effect of human material use on primary producers will most probably be small and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

c) Species introduction/extermination – Humans may affect the settlement of primary producers by active dispersal, introduction or extermination of species. Examples of introduction of species to Swedish lakes and streams are Canadian pondweed (*Elodea Canadensis*, Sw. vattenpest), western water weed (*Elodea nuttallii*, Sw. smal vattenpest), and fringed water-lily (*Nymphoides peltata*, Sw. sjögull) (Olsson 2000, Naturvårdsverket 2007). There are also numerous examples from terrestrial ecosystems. However, although important from an ecological view point, introduction and extermination of species of primary producers are considered to be of minor importance for radionuclide transport and thus do not need to be considered in a safety assessment for a repository at Forsmark.

d) Stimulation/inhibition – The activities of humans may stimulate or inhibit certain species of primary producers. The activities of humans planting and foresting plants can change ecosystem from e.g. forestry to agricultural systems and influence the transport of radionuclides in the ecosystem and needs to be considered in a safety assessment for a repository at Forsmark.

11:7 Humans affect **Decomposers** by the processes a) Consumption, b) Material use, c) Species introduction/extermination, and d) Stimulation/inhibition.

a) Consumption – The feeding by humans on decomposers is assumed to be negligible in Forsmark today but may be an important food pathway in the future (e.g. crayfish fungi, interaction 7:11). However, even if human consumption of decomposers were to increase, the impact on decomposers can be assumed to be small and does not need to be considered in a safety assessment for a repository at Forsmark.

b) Material use – Material use of decomposers by humans is considered an insignificant process and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

c) Species introduction/extermination – Humans may introduce decomposers (e.g. crayfish that are omnivorous) to aquatic environments. For most species, introduction or extermination of species is important from an ecological view point whereas the effect on radionuclide transport is considered minor. However, when introducing species utilised for food by humans, the introduction may have a large impact on the exposure to radionuclides by humans, e.g. introduction of crayfish, and thus this interaction needs to be considered in a safety assessment for a repository at Forsmark.

d) Stimulation/inhibition – The activities of humans may stimulate or inhibit decomposers. The human interference with decomposers is assumed to be small and this interaction therefore does not need to be considered in a safety assessment for a repository at Forsmark.

11:8 Humans affect **filter feeders** in aquatic ecosystems by the processes a) Consumption, b) Material use, c) Species introduction/extermination, and d) Stimulation/inhibition.

a) Consumption – Humans can consume clams and mussels which may be important for exposure (see interaction 8:11). However, the potential consumption of filter feeders by humans is assumed to have a negligible impact on the filter feeder population and does not need to be considered in a safety assessment for a repository at Forsmark.

b) Material use – Humans may use the shells from filter feeders in e.g. handicraft or as nutritional supplements in breeding of domestic birds. However, the use of materials derived from filter feeders is assumed to be small, and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

c) Species introduction/extermination – Humans may introduce filter feeders by cultivation, but it is unlikely that they will exterminate filter feeders due to difficulties in exterminating only certain types of aquatic biota without disturbing the entire ecosystems. Introduction of filter feeders does not need to be considered in a safety assessment for a repository at Forsmark. Although cultivation may greatly influence the aquatic ecosystem from an ecological viewpoint, from the exposure of radionuclides viewpoint, it will not affect the transfer and accumulation of radionuclides in a negative way. Cultivation of filter feeders would decrease concentrations of radionuclides in the ecosystem due to the requirements of food import for the cultivated animals (e.g. pellets) which will dilute the organic matter in the ecosystem. Therefore, as a cautious assumption, introduction of filter feeders does not need to be considered in a safety assessment for a repository at Forsmark.

d) Stimulation/inhibition – The activities of humans may stimulate or inhibit filter feeders. However, it is hard to imagine any human activities that would have a substantial effect on the filter feeder population and thereby significantly influence the transport of radionuclides in the ecosystem. Therefore does not need to be considered in a safety assessment for a repository at Forsmark.

11:9 Humans affect **herbivores** by the processes a) Consumption, b) Material use, c) Species introduction/extermination, and d) Stimulation/inhibition.

a) Consumption – Humans may feed on herbivores (this can be important for exposure see 9:11) and may thereby affect the population of herbivores, e.g. by fishing and hunting, therefore this interaction need to be considered in a safety assessment for a repository at Forsmark.

b) Material use – From terrestrial ecosystems, skins from herbivores may be used for clothing. Also from aquatic ecosystems, it occurs that shoes and various accessories are manufactured from for example fish skin (Rahme and Hartman 2006). However, humans are assumed to apply sustainable hunting and fishing pressure (so that the process can go on). Therefore the effect on herbivores should be small and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

c) Species introduction/extermination – Humans may introduce herbivores to terrestrial (game) and aquatic environments (e.g. crayfish that are omnivorous). For most species, introduction or extermination of species is important from an ecological view point whereas the effect on radionuclide transport is considered to be minor. Exceptions to this are if introduced species cause a cascade effect altering the entire food web (and thereby flux of radionuclides) as happened e.g. in Lake Victoria when Nile perch were introduced (e.g. Goldschmidt et al. 1993). The largest effect of an introduction for the exposure of humans is when the introduced species are utilised for food and this interaction needs to be considered in a safety assessment for a repository at Forsmark.

d) Stimulation/inhibition – The activities of humans may stimulate or inhibit herbivores, e.g. by the use of cattle and sheep in farming. This may determine which and how many herbivores are present at a site and thereby influence the transport of radionuclides in the ecosystem. Therefore this interaction needs to be considered in a safety assessment for a repository at Forsmark.

11:10 Humans affect **carnivores** by the processes a) Consumption, b) Food supply, c) Material use, d) Species introduction/extermination, and e) Stimulation/inhibition.

a) Consumption – The feeding by humans on carnivores is assumed to have a negligible impact on the carnivore populations and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

b) Food supply – In ecosystems at Forsmark there are no carnivores that feed on humans at present. Even if carnivores that could kill and eat humans (e.g. bear) were to occupy Forsmark they are not likely to have humans as a primary food source and this process does not need to be considered in a safety assessment for a repository at Forsmark.

c) Material use – From terrestrial ecosystems, skins from carnivores may be used for clothing. Also from aquatic ecosystems, it occurs that shoes and various accessories are manufactured from for example from fish skin (Rahme and Hartman 2006). However, humans are assumed to apply sustainable hunting fishing pressure (so that the process can go on) and therefore the effect on carnivores should be small and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

d) Species introduction/extermination – Humans may introduce carnivores (e.g. crayfish that are omnivorous) to aquatic environments. For most species, introduction or extermination of species are important from an ecological view point whereas the effect on radionuclide transport is considered to be minor. Exceptions to this are if introduced species cause a cascade effect altering the entire food web (and thereby flux of radionuclides) as happened e.g. in Lake Victoria when Nile perch were introduced (e.g. Goldschmidt et al. 1993). However, the largest effect for the safety assessment is when introduced species are utilised as food, which may have a large impact on the exposure to radionuclides by humans and thus this interaction needs to be considered in a safety assessment for a repository at Forsmark.

e) Stimulation/inhibition – The activities of humans may stimulate or inhibit carnivores, e.g. by hunting. However, humans are assumed to apply sustainable hunting fishing pressure (so that the process can go on) and therefore the effect on carnivores should be small and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

11:11 Humans is a diagonal element further described in Chapter 4. Humans is internally affected by the features Geometry, Material composition and Radionuclide inventory. Humans affect each other by the processes: a) Exposure, b) Growth, c) Radioactive decay, and d) Stimulation/inhibition.

a) Exposure – Exposure can either be external due to sources outside the body or internal due to sources inside the body. Concentration, location and type of radionuclides in surface waters, regolith, and in the atmosphere, i.e. in all parts of the biosphere system, affect the external exposure of, and the radiologic and toxic effects on, humans. Concentrations within humans affect the internal dose. This interaction needs to be considered in a safety assessment for a repository at Forsmark.

b) Growth – The growth and life span of humans affect the concentrations of radionuclides in humans and this interaction needs to be considered in a safety assessment for a repository at Forsmark.

c) Radioactive decay – Radionuclides in the different biosphere components undergo radioactive decay where they transform into other radionuclides or form stable isotopes. Consideration of decay of radionuclides within diagonal components is important in estimating the amounts of different radionuclides in the biosphere and this process needs to be considered in a safety assessment for a repository at Forsmark.

d) Stimulation/inhibition – Humans may interact in many ways. However, in the safety assessment, maximum sustainable use of the ecosystem is assumed and no further considerations are needed.

11:12 Humans affect **external conditions** by the process a) Export.

a) Export – Humans influence the external conditions by exporting themselves (i.e. migration), exporting material, heat and radionuclides.
   - The effect on external conditions by humans moving out of the repository area is assumed to be small (i.e. the migration of people from Forsmark will be small compared to the human population outside Forsmark) and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.
   - Humans may harvest and export matter (and energy) from an ecosystem at Forsmark to external locations. The effect on the receiving system is assumed to be of minor importance compared to the effect on ecosystems within the assessment domain and this interaction does not need to be considered in a safety assessment for a repository at Forsmark.
   - The export of heat is regarded as quantitatively unimportant for the external conditions (i.e. surrounding ecosystem and atmosphere). Humans may affect the global climate but this is not due only the persons living in a small area (e.g. the model area in Forsmark). Thus, climate conditions have to be considered, but this specific interaction does not need to be considered in a safety assessment for a repository at Forsmark.

12:1 External conditions affect **geosphere** by the process a) Change in rock-surface location.

a) Change in rock-surface location – At a large-scale, glaciation influences the regolith and geosphere by isostatic compression and rebound. Presently interglacial conditions prevail and there is an isostatic rebound that results in land-rise and new land (regolith) emerging from the sea. The uplift of land results in shoreline-displacement which is an important interaction to consider in a safety assessment for a repository at Forsmark. Other examples of changes in rock surface location are those due to earthquakes. These are treated in the geosphere part of the safety assessment.

12:2 External conditions affect **the regolith** by the processes a) Change in rock-surface location, b) Import, and c) Light-related processes.

a) Change in rock-surface location – At a large-scale, glaciation influences the regolith and geosphere by isostatic compression and rebound. Presently interglacial conditions prevail and there is an isostatic rebound that results in land-rise and new land (regolith) emerging from the sea. The uplift of land results in shoreline-displacement which is an important interaction to consider in a safety assessment for a repository at Forsmark.

b) Import – regolith, heat, and radionuclides, may be transported from external location into the regolith of the model area,
   - The redistribution of regolith due to glacial processes is important for the amounts of regolith in the model area and should be considered in a safety assessment for a repository at Forsmark. Import of regolith from areas outside the model object may also be important to consider within the glacial periods, e.g. import of regolith during sea period due to resuspension and sedimentation. This interaction needs to be considered but redistribution within glaciations does not.
   - Import of heat by different materials entering the system will influence the temperature in the different elements of the system. This interaction is assumed to be a forcing function for the temperature in the system and needs to be considered in a safety assessment for a repository at Forsmark.
   - In a safety assessment it can be assumed that the only source of radionuclides is internal from within the radioactive waste, i.e. radionuclides from natural background or from other repositories do not have to be considered but should be treated separately. Thus, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.

c) Light-related processes – Insolation and other sources of irradiation entering the system influence the temperature in the different parts of the system. Climate and temperature will have strong effect on functioning of ecosystems and this interaction needs to be considered in a safety assessment for a repository at Forsmark.

12:3 External conditions affect **water in regolith** by the processes a) Import, b) Light-related processes, and c) Saturation.

a) Import – Water, radionuclides, heat and other elements may be transported from external locations into the model area.
   - Inflow of water to regolith from water in regolith outside the studied ecosystem is important for the water flow and thereby transport and accumulation of radionuclides. Thus, this interaction needs to be considered in a safety assessment for a repository at Forsmark.
   - Import of heat by different materials entering the system will influence the temperature in the different elements of the system. This interaction is assumed to be a forcing function for the temperature in the system and needs to be considered in a safety assessment for a repository at Forsmark.
   - In a safety assessment it can be assumed that the only source of radionuclides is internal from within the radioactive waste, i.e. radionuclides from natural background or from other repositories do not have to be considered but should be treated separately. Thus, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.
   - The composition of surrounding waters outside the ecosystem may, by import, affect the composition of the surface waters and water in the regolith. The surrounding ecosystems have a large effect on the chemical composition of their included waters and thus this interaction needs to be considered in a safety assessment for a repository at Forsmark.

b) Light-related processes – Insolation and other sources of irradiation entering the system influence the temperature in the different parts of the system. Climate and temperature will have strong effect on functioning of ecosystems and this interaction needs to be considered in a safety assessment for a repository at Forsmark.

c) Saturation – External factors (e.g. climate) may influence the groundwater level in the regolith. This may be important for the water flow and thereby transport and accumulation of radionuclides. Thus, this interaction needs to be in a safety assessment for a repository at Forsmark.

12:4 External conditions affect **surface waters** by the processes a) Convection, b) Import, c) Light-related processes, and d) Sea-level change.

a) Convection – External factors such as wind fields and the rotation of the earth are some of the driving forces for water turnover of the sea. Likewise, discharge from upstream catchments influences water movements in lakes, streams and wetlands. This interaction need to be considered in a safety assessment for a repository at Forsmark.

b) Import – Water, radionuclides, heat and other elements may be transported from external locations into the model area.
   - Precipitation is a major factor determining the discharge into streams, lakes and marine basins. This is one of the major determinants of the water retention time and therefore needs to be considered in a safety assessment for a repository at Forsmark.
   - Import of heat by different materials entering the system will influence the temperature in the different elements of the system. This interaction is assumed to be a forcing function for the temperature in the system and needs to be considered in a safety assessment for a repository at Forsmark.
   - In a safety assessment it can be assumed that the only source of radionuclides is internal from within the radioactive waste, i.e. radionuclides from natural background or from other repositories do not have to be considered but should be treated separately. Thus, this interaction does not need to be considered in a safety assessment for a repository at Forsmark.
   - The composition of surrounding waters outside the ecosystem may, by import, affect the composition of the surface waters and water in the regolith. The surrounding ecosystems have a large effect on the chemical composition of their included waters and thus this interaction needs to be considered in a safety assessment for a repository at Forsmark.

c) Light-related processes – Insolation and other sources of irradiation entering the system influence the temperature in the different parts of the system. Climate and temperature will have strong effect on the functioning of ecosystems and this interaction needs to be considered in a safety assessment for a repository at Forsmark.

d) Sea-level change – Sea-level changes can be caused by e.g. earthquakes (tsunamis), global warming, land-slides, earth tides, weather and climatic changes. The alteration in height of the sea relative to the land will affect the amount and movement of surface waters. The distribution of surface waters is important for transport and accumulation of radionuclides and this interaction needs to be considered in a safety assessment for a repository at Forsmark.

12:5 External conditions affect **gas and local atmosphere** by the processes a) Import, b) Light-related processes and c) Reactions.

a) Import – The local atmosphere is influenced by large-scale weather systems and solar insolation. The interactions between external conditions and the local atmosphere may have a large effect on the transport and accumulation of radionuclides and this interaction needs to be considered in a safety assessment for a repository at Forsmark.

b) Light-related processes – Insolation and other sources of irradiation entering the system influence the temperature in the different parts of the system. Climate and temperature will have strong effect on functioning of ecosystems and this interaction needs to be considered in a safety assessment for a repository at Forsmark.

c) Reactions – Photo-chemical reactions close to the surface will affect the gas composition e.g. ozone formation, smog formation and reactions in exhaust gases. This is assumed to have insignificant effect on radionuclide transport and does not need to be considered in a safety assessment for a repository at Forsmark.

12:6 External conditions affect **primary producers** by the processes a) Import, b) Light-related processes and c) Stimulation/inhibition.

a) Import – Import of plants and seeds may occur naturally by e.g. spreading of seeds with the wind, and by human plantation. The import of organisms may affect the accumulation and transfer of radionuclides by increasing the biomass and thus needs to be considered in a safety assessment for a repository at Forsmark.

b) Light-related processes – The amount of solar irradiation influences photosynthesis and thereby the type and amount of primary producers. This interaction may be important for the accumulation and transport of radionuclides into the food web and needs to be considered in a safety assessment for a repository at Forsmark.

c) Stimulation/inhibition – Temperature influences the pattern of settlement, e.g. extreme temperatures prevent biota from utilizing very cold environments. This can have an effect on transport and accumulation of radionuclides and needs be considered in a safety assessment for a repository at Forsmark.

12:7 External conditions affect **decomposers** by the processes a) Import and b) Stimulation/inhibition.

a) Import – The import of organisms may affect the accumulation and transfer of radionuclides by increasing the biomass and thus, needs to be considered in a safety assessment for a repository at Forsmark.

b) Stimulation/inhibition – Temperature influences the pattern of settlement, e.g. extreme temperatures prevent biota from utilizing very cold environments. This can have an effect on transport and accumulation of radionuclides and needs be considered in a safety assessment for a repository at Forsmark.

12:8 External conditions affect **filter feeders** by the processes a) Import and b) Stimulation/inhibition.

a) Import – The import of organisms may affect the accumulation and transfer of radionuclides by increasing the biomass and thus, needs to be considered in a safety assessment for a repository at Forsmark.

b) Stimulation/inhibition – Temperature influences the pattern of settlement, e.g. extreme temperatures prevent biota from utilizing very cold environments. This can have an effect on transport and accumulation of radionuclides and needs be considered in a safety assessment for a repository at Forsmark.

12:9 External conditions affect **herbivores** by the processes a) Import and b) Stimulation/inhibition.

a) Import – The import of organisms may affect the accumulation and transfer of radionuclides by increasing the biomass and thus, needs to be considered in a safety assessment for a repository at Forsmark.

b) Stimulation/inhibition – Temperature influences the pattern of settlement, e.g. extreme temperatures prevent biota from utilizing very cold environments. This can have an effect on transport and accumulation of radionuclides and needs be considered in a safety assessment for a repository at Forsmark.

12:10 External conditions affect **carnivores** by the processes a) Import and b) Stimulation/inhibition.

a) Import – The import of organisms may affect the accumulation and transfer of radionuclides by increasing the biomass and thus, needs to be considered in a safety assessment for a repository at Forsmark.

b) Stimulation/inhibition – Temperature influences the pattern of settlement, e.g. extreme temperatures prevent biota from utilizing very cold environments. This can have an effect on transport and accumulation of radionuclides and needs be considered in a safety assessment for a repository at Forsmark.

12:11 External conditions affect **humans** by the process a) Import, and b) Stimulation/inhibition.

a) Import – The import of uncontaminated material by humans to the contaminated area may reduce the dose in a safety assessment. If using cautious assumptions on human behaviour the import of material does not need to be considered in a safety assessment for a repository at Forsmark.

b) Stimulation/inhibition – Temperature influences the pattern of settlement, e.g. extreme temperatures prevent humans from utilizing all parts of the ecosystem. This may have an effect on the exposure of humans and needs be considered in a safety assessments for a repository at Forsmark. Other factors, e.g. socio-economic factors may also affect human settlement in the model area, this area belong to Future Human action and not specifically biosphere assessment at SKB.

12:12 External conditions are a diagonal element defined as all global conditions that affect local conditions that are considered in the biosphere matrix. The external conditions are situated at the boundary of the biosphere matrix and processes by which the external factors influence each other are not described here. Global climate change should be considered. Other factors, e.g. socio-economic factors may also affect human settlement in the model area, this area belong to Future Human action and not specifically biosphere assessments at SKB. Also, other more catastrophic events, such as meteorite impacts or human intrusion scenarios could be considered separately. To ensure comprehensive handling of such global events, the SKB list of FEPs is checked against international FEP list and reviewed by experts in the field.

8 Concluding discussion

Not all processes between the components in the IM are expected to be quantitatively important for transport and accumulation of radionuclides from a geological repository in Forsmark. Thus, of the 50 identified processes, 45 were judged as necessary for inclusion in the safety assessment, either due to direct effects on transport of radionuclides or due to indirect effects on radionuclide distribution due to their influence on landscape development or ecosystem functioning (Table 8-1). These processes may be necessary to consider in some specific interactions but not in others (Table 8-1, Figure 8-1 and 8-2, Appendix A and B). For a detailed description of why it was considered necessary to include specific processes in respect of a particular interaction, the reader is referred to Chapter 7. A general description of these important processes is presented below. The processes judged to be insignificant and not necessary to include in the safety assessment are movement, loading, change of pressure, irradiation and radiolysis.

There are many biological processes that it is judged necessary to consider in the assessment. This is because the most important exposure pathway for humans is via intake of water and food. Thus, it is important to consider the distribution of biota and food-web interactions. In addition, biota may influence the distribution of radionuclides in abiotic pools by e.g. disturbing sediment or affecting water composition, thereby influencing the long-term accumulation and transport of radionuclides. However, other groups of processes are equally important to consider (as further explored below).

Consumption, death, decomposition, excretion, food supply, habitat supply, stimulation/inhibition, and uptake, are biotic processes that may influence transport and accumulation of radionuclides in the food web. The processes bioturbation and particle release/trapping influence the abiotic components of the environment. Bioturbation influences the properties of the regolith and may thereby influence the accumulation of radionuclides in it. Particle release/trapping influences the amounts of particles in water and air, which is important for the transport of radionuclides adherring to those particles.

Human behaviour may have large effect on the biosphere e.g. by introducing species or elements or by disturbing or removing material in large quantities. Water use, anthropogenic release, and species introduction/extermination are processes related to human behaviour that needs to be considered in a safety assessment.

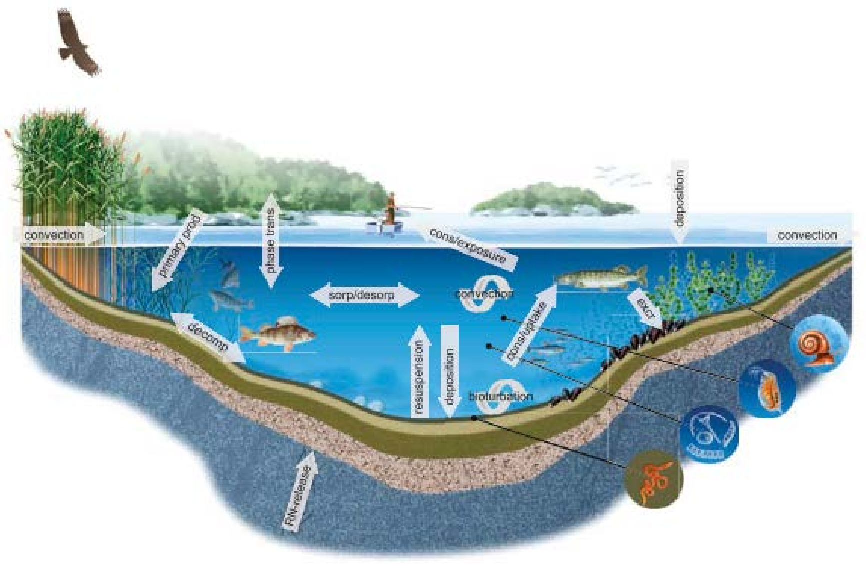

Figure 8-1. Example of an ecosystem model: a conceptual model of an aquatic ecosystem. Arrows illustrate processes (e.g. consumption, excretion and convection) whereby different components of the aquatic ecosystem affect each other. Abbreviations are as follows: cons.=consumption, decomp.=decomposition, excr.=excretion,phase trans.=phase transitions, RNrelease= radionuclide release, sorp./desorp.=sorption/desorption.

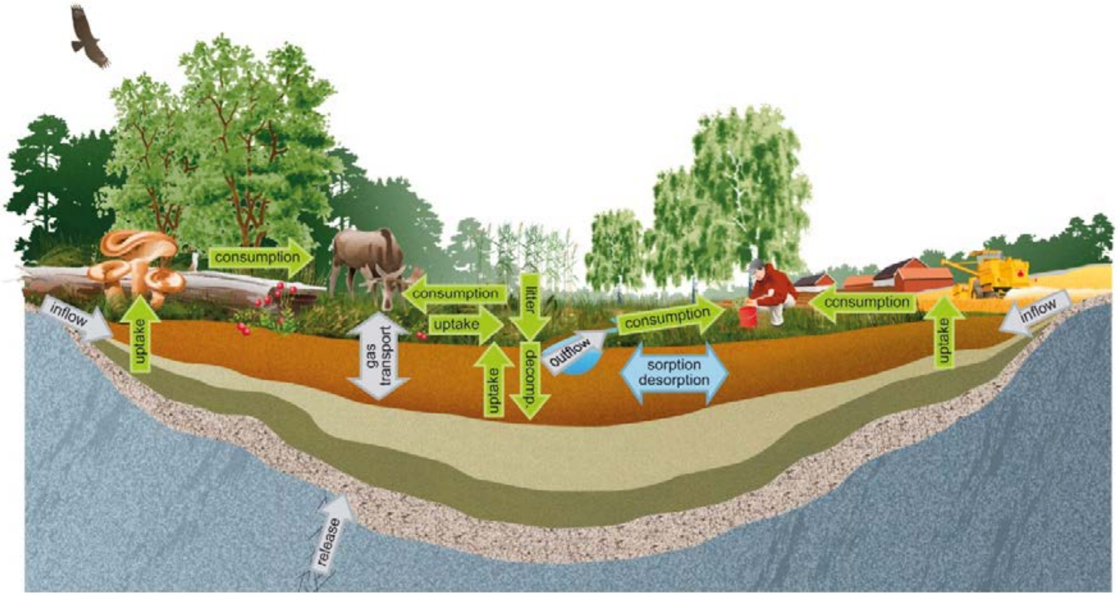

Figure 8-2. A conceptual representation of important fluxes affecting the transport and accumulation of elements in a wetland ecosystem and in arable land on a drained part of a mire, where human exposure is an important consideration in the safety assessment. Green arrows are fluxes mediated by biota, grey arrows are water and gas fluxes, the blue arrow represents sorption/desorption processes, and consumption also includes water for drinking. The mire was preceded by a lake and a marine stage in which gyttja/clay and postglacial clay were deposited prior to the peat.

Chemical, mechanical and physical processes can influence the state of elements and compounds, which can be important for the transport of radionuclides. For example, in some states elements are tightly bound to particles and in other states they may be easily dissolved and transported with water. Chemical, mechanical and physical processes that have to be considered in the radionuclide transport modelling are; phase transitions and sorption/desorption. The process phase transitions is important for transport of C-14 from water to air. The process sorption/desorption determines whether radionuclides are bound to surfaces or dissolved in water and is crucial to determining the transport and biological uptake of radionuclides.

Transport processes that it is necessary to consider in a safety assessment for a geological repository are; convection, deposition, import, resuspension, relocation and saturation. Convection includes e.g. surface water flow, discharge and recharge. Discharge and recharge are important for the transport upwards from a repository to surface systems and the pattern of discharge vs. recharge is important for the understanding of why and how transport of deep groundwater occurs. Surface water flow is also important for relocation of radionuclides, since relatively fast transport through the landscape can take place in surface waters compared with groundwater and may affect the retention times in water bodies. In addition, flooding may cause a redistribution of radionuclides in the landscape. Radionuclides that have reached the surface system can, via recharge, go back to the groundwater system again. Import is the transport of radionuclides from surrounding ecosystems. This process may be of importance for the amounts of radionuclides in an ecosystem. The processes resuspension, relocation and deposition (e.g. sedimentation) are important for the transport from sediment to the water column and vice versa. Deposition is, in addition to sedimentation, also used to describe precipitation, which is important for water balances and surface water flows.

Thermal and radiological processes that have to be considered in a safety assessment are; radioactive decay, exposure, heat storage, and light-related processes. Radionuclide-specific characteristics influence the transport of radionuclides and are of course important to consider in the radionuclide modelling. The amounts of radionuclides released (radionuclide release), radioactive decay and exposure are crucial for the safety analysis. The process heat storage has a great influence on both biotic and abiotic components of ecosystems influencing e.g. the distribution of biota, mixing of the water column, and ice coverage preventing exchange over the air-water interface. Light-related processes include insolation, light absorption, light reflection and light scattering which in turn influence primary production.

Finally, the type of ecosystem greatly influences transport and accumulation of radionuclides. Landscape development processes that need to be considered in the radionuclide modelling are change in rock surface location, sea-level change, and thresholding. These processes determine the ecosystem at the site, e.g. terrestrial, limnic or marine (i.e. the featured stage of succession).

Summarising the essence of this Chapter, it illustrates major process interactions and identifies processes that are necessary to consider in safety assessments, either directly in radionuclide transport models or in underlying models describing ecosystem functioning.

Table 8-1. Process interactions identified as important to consider in a safety assessment for a repository at Forsmark.

Process	Definition	Interactions in the matrix (read row:column)	Numbering in SKBs FEP data base
Biological processes			
Bioturbation	The mixing of elements and particles in both aquatic and terrestrial regolith by organisms.	6:2, 7:2	Bio01
Consumption	When organisms feed on solid material and/or on other organisms.	7:2, 7:4, 8:4, 8:6, 8:7, 9:6, 10:7, 10:8, 10:9, 10:10, 11:9	Bio02
Death	The generation of dead organic matter by organisms.	6:2, 6:4, 7:2, 7:4, 8:2, 8:4, 9:2, 9:4	Bio03
Decomposition	The breakdown of organic matter by organisms.	7:2, 7:4	Bio04
Excretion	The excretion of water or elements to the surrounding media by humans and other organisms.	6:3, 6:4, 6:5, 7:2, 7:3, 7:4, 7:5, 8:3, 8:4, 9:2, 9:3, 9:4, 9:5, 10:2, 10:3, 10:4, 10:5	Bio05
Food supply	The fraction of produced biomass and particulate matter that can be used as a food source for humans and other organisms.	2:7, 2:11, 4:8, 6:8, 6:9, 6:11, 7:8, 7:10, 7:11, 8:10, 8:11, 9:10, 9:11, 10:10, 10:11	Bio06
Growth	The generation of biomass by organisms.	6:6, 7:7, 8:8, 9:9, 10:10, 11:11	Bio07
Habitat supply	The providing of habitat for organisms by abiotic elements or other organisms.	2:6, 2:7, 2:8, 2:9, 2:10, 2:11, 4:6, 4:7, 4:8, 4:9, 4:10, 4:11	Bio08
Intrusion	Non-human organisms or humans enter the repository, for example by locomotion, drilling or growth.	11:1	Bio09
Material supply	The amount of material that is available for human utilisation for purposes other than feeding.	2:11, 6:11	Bio10
Particle release/trapping	Organisms release particles (for example by fragmentation, spawning and pollen release) or trap particles (for example with gills, feathers and slime).	8:4	Bio12
Primary production	The fixation of carbon by primary producers in photosynthesis.	6:6	Bio13
Stimulation/inhibition	When one diagonal element positively or negatively influences another diagonal element. The extreme of inhibition prevents settlement and leads to exclusion from the associated model areas.	2:6, 2:7, 2:8, 2:9, 2:10, 2:11, 3:6, 3:7, 3:8, 3:9, 3:10, 3:11, 4:6, 4:7, 4:8, 4:9, 4:10, 4:11, 5:6, 5:7, 5:9, 5:10, 5:11, 11:6, 11:9, 12:6, 12;7, 12:8, 12:9, 12:10, 12:11	Bio14
Uptake	The incorporation of water or elements from the surrounding media into humans and other organisms.	6:3, 6:4, 6:5, 7:3, 7:4, 7:5, 8:4, 9:2, 9:3, 9:4, 9:5, 10:2, 10:3, 10:4, 10:5, 11:3, 11:4, 11:5	Bio15

Process	Definition	Interactions in the matrix (read row:column)	Numbering in SKBs FEP data base
Processes related to human behaviour			
Anthropogenic release	Release caused by humans of substances, water or energy into the local biosphere.	11:2, 11:3, 11:4, 11:5	Bio16
Material use	Human utilisation of the environment for purposes other than feeding.	11:2	Bio17
Species introduction/ extermination	Introduction or extermination of species from the model area by human activities (e.g. introduction of crayfish in lakes).	11:7, 11:9, 11:10	Bio18
Water use	Water use by humans for purposes other than drinking, e.g. washing, irrigation and energy production.	11:3, 11:4	Bio19
Chemical, mechanical and physical processes			
Consolidation	Any process whereby loosely aggregated, soft, or liquid earth materials become firm and coherent rock or the compactation of regolith.	2:2; 11:2	Bio 21
Element supply	The availability of elements and substances for use by organisms.	2:6, 2:7, 3:6, 3:7, 4:6, 4:7, 4:9, 4:10, 5:6	Bio22
Phase transitions	Changes between different states of matter: solid, liquid and gas.	3:2, 3:3, 3:5, 4:4, 4:5, 5:4	Bio24
Physical properties change	Changes in volume, density, porosity, and/or viscosity.	2:2, 4:4	Bio25
Reactions	Chemical reactions excluding weathering, decomposition and photosynthesis.	2:3, 3:3, 4:4	Bio26
Sorption/desorption	Dissolved substances adhere to surfaces or are released from surfaces.	2:3, 2:4, 3:2, 4:2, 4:4, 5:5, 6:3, 6:4, 6:5, 7:3, 7:4, 7:5, 8:2, 8:3, 8:4, 9:2, 9:3, 9:4, 9:5, 10:2, 10:3, 10:4, 10:5	Bio27
Water supply	The amount of water available for drinking and other uses by humans and other organisms.	1:11, 3:6, 3:11, 4:6, 4:11	Bio28
Weathering	Disintegration of solid matter into smaller pieces.	2:2	Bio29
Wind stress	A mechanical force generated by wind affecting the biosphere.	5:4	Bio30
Transport processes			
Acceleration	The change in velocity of a fluid or body over time and/or the rate and direction of velocity change. May be either positive or negative (retardation).	6:5, 11:4	Bio31
Convection	The transport of a substance or a conserved property with a fluid or gas.	1:3, 1:4, 1:5, 2:3, 3:1, 3:3, 3:4, 4:1, 4:3, 4:4, 5:3, 5:4, 5:5, 12:4	Bio32
Covering	The covering of surface water by e.g. vegetation or ice that reduces light and prevents the exchange of gases and particles between the water and the atmosphere.	4:5	Bio33

Process	Definition	Interactions in the matrix (read row:column)	Numbering in SKBs FEP data base
Deposition	Vertical transfer of a material or element to a surface of any kind due to gravitation, e.g. sedimentation, rainfall, and snowfall.	4:2, 5:4	Bio34
Export	Transport out of the model area.	3:12, 4:12, 5:12, 6:12	Bio35
Import	Transport into the model area.	12:2, 12:3, 12:4, 12:5, 12:6, 12:7, 12:8, 12:9, 12:10	Bio36
Interception	The amount of precipitation that does not reach the ground but is retained on vegetation.	6:4	Bio37
Relocation	The horizontal transport of solid matter and sessile organisms from one point to another.	4:2, 11:2	Bio38
Resuspension	The stirring up of previously settled particles in water or air.	2:4, 2:5, 4:2	Bio39
Saturation	Water content that affects physical and chemical properties of the regolith.	3:2, 4:2, 12:3	Bio40
Radiological and thermal processes			
Radioactive decay	The physical transformation of radionuclides to other radionuclides or stable elements.	2:2, 2:5, 3:3, 3:5, 4:4, 5:5, 6:6, 7:7, 8:8, 9:9, 10:10, 11:11	Bio41
Exposure	The act or condition of being subject to irradiation. Exposure can either be external exposure from sources outside the body or internal exposure from sources inside the body.	2:6, 2:7, 2:8, 2:9, 2:10, 2:11, 3:6, 3:7, 3:8, 3:9, 3:10, 3:11, 4:6, 4:7, 4:8, 4:9, 4:10, 4:11, 5:6, 5:7, 5:8, 5:9, 5:10, 5:11, 6:6, 7:7, 8:8, 9:9, 10:10, 11:11	Bio42
Heat storage	The storage of heat in solids and water.	4:4	Bio43
Light-related processes	Processes related to the light entering the biosphere (insolation), e.g. absorption, attenuation, reflection and scattering.	4:4, 4:6, 12:2, 12:3, 12:4, 12:5, 12:6	Bio45
Radionuclide release	Release of radionuclides from the repository.	1:1	Bio47
Landscape development processes			
Change in rock surface location	Changes in the location of the rock surface due to isostatic rebound or repository-induced changes.	12:1, 12:2	Bio48
Sea-level change	Alteration in the level of the sea relative to the land.	12:4	Bio49
Thresholding	The occurrence and location of thresholds delimits lakes and sea basins.	2:3, 2:4, 2:12	Bio50

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Biosphere interaction matrix

	1	2	3	4	5	6	7	8	9	10	11	12
1	**GEOSPHERE (B.C.)**	a)Change in rock surface location b)Convection c)Weathering	a) Convection	a)Convection	a)Convection						a)Material supply b) Water supply	
2	a)Consolidation b)Convection c)Loading	**Regolith** *Geometry *Material composition *RN inventory *Stage of succession *Temperature*Water composition	a)Convection b)Phase transitions c)Reactions d)Sorption/Desorption e)Thresholding	a)Acceleration b)Phase transitions c)Reactions d)Resuspension e)Sorption/desorption f)Thresholding	a)Acceleration b)Change of pressure c)Phase transitions d)Radioactive decay e)Reactions f)Resuspension	a)Element supply b)Exposure c)Habitat supply d)light-related processes e)Relocation f)Stimulation/inhibition	a)Element supply b)Exposure c)Food supply d)Habitat supply e)Stimulation/inhibition	a)Exposure b)Habitat supply c)Stimulation/inhibition	a)Exposure b)Habitat supply c)Stimulation/inhibition	a)Exposure b)Habitat supply c)Stimulation/inhibition	a)Exposure b)Food Supply c)Habitat supply d)Material supply e)Stimulation/inhibition	a)Export b)Thresholding
3	a)Change of pressure b)Convection c)Weathering	aPhase transitions b)Relocation c)Saturation d)Sorption/desorption e)Weathering	**Water in regolith** *Geometry *Material composition *RN inventory *Stage of succession *Temperature*Water composition	a)Convection	a)Decay b)Phase transitions	a)Element supply b)Exposure c)Habitat supply d)Stimulation/inhibition e)Water supply	a)Element supply b)Exposure c)Habitat supply d)Stimulation/inhibition e)Water supply	a)Exposure b)Stimulation/inhibition c)Water supply	a)Exposure b)Stimulation/inhibition c)Water supply	a)Exposure b)Stimulation/inhibition c)Water supply	a)Exposure b)Stimulation/inhibition c)Water supply	a) Export
4	a)Change of pressure b)Convection c)Loading d)Weathering	a)Deposition b)Relocation c)Resuspension d)Saturation e)Sorption/desorption f)Weathering	a) Convection	**Surface water** *Geometry *Material composition *RN inventory *Stage of succession *Temperature*Water composition	a)Covering b)Phase transition c)Relocation d)Resuspension	a)Element supply b)Exposure c)Habitat supply d)light-related processes e)Relocation f)Stimulation/inhibition g)Water supply	a)Element supply b)Exposure c)Food supply d)Habitat supply e)Relocation f)Stimulation/inhibition g)Water supply	a)Element supply b)Exposure c)Food supply d)Habitat supply e)Relocation f)Stimulation/inhibition g)Water supply	a)Element supply b)Exposure c)Habitat supply d)Relocation e)Stimulation/inhibition f)Water supply	a)Element supply b)Exposure c)Habitat supply d)Relocation e)Stimulation/inhibition f)Water supply	a)Exposure b)Habitat supply c)Stimulation/inhibition d)Water supply	a)Export b)Import
5	a)Convection	a)Deposition b)Reactions c)Relocation d)Resuspension	a) Convection b)Phase transitions	a)Convection b)Deposition c)Phase transitions d)Wind stress	**Local atmosphere** *Geometry *Material composition *RN inventory *Stage of succession *Temperature*Water composition	a)Element supply b)Exposure c)Relocation d)Stimulation/inhibition	a)Element supply b)Exposure c)Stimulation/inhibition	a)Element supply b)Exposure c)Stimulation/inhibition	a)Element supply b)Exposure c)Stimulation/inhibition	a)Element supply b)Exposure c)Stimulation/inhibition	a)Deposition b)Element supply c)Exposure d)Stimulation/inhibition	a)Export
6	a)Intrusion	a)Bioturbation b)Convection c)Death d)light-related processes e) Reactions	a)Convection b)Excretion c)light-related processes d)Reactions e)Sorption/desorption f)Uptake	a)Acceleration b)Convection c)Covering d)Death e)Excretion f)Interception g)light-related processes h)Reactions i)Particle release/trapping j)Sorption/desorption k)Uptake	a)Acceleration b)Covering c)Excretion d)light-related processes e)Reactions f)Particle release/trapping g)Sorption/desorption h)Uptake	**Primary producers** *Geometry *Material composition *RN inventory *Stage of succession *Temperature*Water composition	a)Habitat supply b)Stimulation/inhibition	a)Food supply b)Habitat supply c)Stimulation/inhibition	a)Food supply b)Habitat supply c)Stimulation/inhibition	a)Stimulation/inhibition	a)Food supply b)Material supply c)Stimulation/inhibition	a)Export
7	a) Intrusion	a)Bioturbation b)Consumption c)Convection d)Death e)Decomposition f)Excretion g)light-related processes h)Reactions	a)Convection b)Decomposition c)Excretion d)light-related processes e)Reactions f)Sorption/desorption g)Uptake	a)Acceleration b)Consumption c)Death d)Decomposition e)Excretion f)light-related processes g)Movement h)Particle release/trapping i)Reactions j)Sorption/desorption k)Uptake	a)Excretion b)light-related processes c)Particle release/trapping d)Reactions e)Sorption/desorption f)Uptake	a)Stimulation/inhibition	**Decomposers** *Geometry *Material composition *RN inventory *Stage of succession *Temperature*Water composition	a) Food supply b) Stimulation/inhibition	a)Stimulation/inhibition	a)Food supply b)Stimulation/inhibition	a)Food supply b)Material supply c)Stimulation/inhibition	a) Export
8	a) Intrusion	a) Bioturbation b)Convection c)Death d)light-related processes e)Reactions f)Sorption/desorption	a)Convection b)Excretion c)light-related processes d)Reactions e)Sorption/desorption f)Uptake	a)Acceleration b)Consumption c)Death d)Excretion e)light-related processes f)Movement g)Particle release/trapping h)Reactions i)Sorption/desorption j)Uptake	a)Excretion b)Uptake	a)Consumption b)Habitat supply c)Stimulation/inhibition	a)Consumption b)Habitat supply c)Stimulation/inhibition	**Filter feeders** *Geometry *Material composition *RN inventory *Stage of succession *Temperature*Water composition	a)Consumption b)Stimulation/inhibition	a)Consumption b)Food supply c)Stimulation/inhibition	a)Food supply b)Material supply c)Stimulation/inhibition	a) Export
9	a) Intrusion	a) Bioturbation b)Convection c)Death d)Excretion e)light-related processes f)Reactions g)Sorption/desorption h)Uptake	a)Convection b)Excretion c)light-related processes d)Reactions e)Sorption/desorption f)Uptake	a)Acceleration b)Death c)Excretion d)light-related processes e)Movement f)Particle release/trapping g)Reactions h)Sorption/desorption i)Uptake	a)Excretion b)light-related processes c)Particle release/trapping d)Reactions e)Sorption/desorption f)Uptake	a)Consumption b)Stimulation/inhibition	a)Stimulation/inhibition	a)Food supply b)Stimulation/inhibition	**Herbivores** *Geometry *Material composition *RN inventory *Stage of succession *Temperature*Water composition	a)Food supply b)Stimulation/inhibition	a)Food supply b)Material supply c)Stimulation/inhibition	a) Export
10	a) Intrusion	a)Bioturbation b)Consolidation c)Convection d)Death e)Excretion f)light-related processes g)Reactions h)Sorption/desorption i)Uptake	a)Convection b)Excretion c)light-related processes d)Reactions e)Sorption/desorption f)Uptake	a)Death b)Excretion c)light-related processes d)Movement e)Particle release/trapping f)Reactions g) Sorption/desorption h)Uptake	a)Excretion b)light-related processes c)Particle release/trapping d)Reactions e)Sorption/desorption f)Uptake	a)Stimulation/inhibition	a)Consumption b)Stimulation/inhibition	a)Consumption b)Food supply c)Stimulation/inhibition	a)Consumption b)Stimulation/inhibition	**Carnivores** *Geometry *Material composition *RN inventory *Stage of succession *Temperature*Water composition	a)Consumption b)Food supply c)Material supply d)Stimulation/inhibition	a) Export
11	a)Intrusion b)Material use	a)Anthropogenic release b)Consolidation c)Consumption d)Convection e)Death f)Excretion g)Material use h)Relocation i)Sorption/desorption	a)Anthropogenic release b)Convection c)Excretion d)Uptake e)Water use	a)Acceleration b)Anthropogenic release c)Covering d)Death e)Excretion f)Movement g)Particle release trapping h)Sorption/desorption i)Uptake j)Water use	a)Acceleration b)Anthropogenic release c)Convection d)Excretion e)light-related processes f)Reactions g)Sorption/desorption h)Uptake	a)Consumption b)Material use c)Species introduction/extermination d)Stimulation/inhibition	a)Consumption b)Material use c)Species introduction/extermination d)Stimulation/inhibition	a)Consumption b)Material use c)Species introduction/extermination d)Stimulation/inhibition	a)Consumption b)Material use c)Species introduction/extermination d)Stimulation/inhibition	a)Consumption b)Food supply c)Material use d)Species introduction/extermination e)Stimulation/inhibition	**Humans** *Geometry *Material composition *RN inventory	a)Export
12	a)Change in rock surface location	a)Change in rock surface location b)Import c)light-related processes	a) Import b)light-related processes c)Saturation	a)Convections b)Import c)light-related processes d)Sea-level change	a)Import b)light-related processes c)Reactions	a)Import b)light-related processes c)Stimulation/inhibition	a)Import b)Stimulation/inhibition	a)Import b)Stimulation/inhibition	a)Import b)Stimulation/inhibition	a)Import b)Stimulation/inhibition	a)Import b)Stimulation/inhibition	**External conditions**

Biosphere interaction matrix showing processes interactions needed to considered in a safety assessment for a geological repository at Forsmark

	1	2	3	4	5	6	7	8	9	10	11	12
1	**GEOSPHERE (B.C.)**		a) Convection	a)Convection	a)Convection						b) Water supply	
2		**Regolith** *Geometry *Material composition *RN inventory *Stage of succession *Temperature*Water composition	a)Convection c) Reactions d)Sorption/Desorption e)Thresholding	d)Resuspension e)Sorption/desorption f)Thresholding	c) Decay e)Resuspension	a)Element supply b)Exposure c)Habitat supply f)Stimulation/inhibition	a)Element supply b)Exposure c)Food supply d)Habitat supply e)Stimulation/inhibition	a)Exposure b)Habitat supply c)Stimulation/inhibition	a)Exposure b)Habitat supply c)Stimulation/inhibition	a)Exposure b)Habitat supply c)Stimulation/inhibition	a)Exposure b)Food Supply c)Habitat supply d)Material supply e) Stimulation/inhibition	b)Thresholding
3	b)Convection	aPhase transitions c)Saturation d)Sorption/desorption	**Water in regolith** *Geometry *Material composition *RN inventory *Stage of succession *Temperature*Water composition	a)Convection	a)Decay b)Phase transitions	a)Element supply b)Exposure d)Stimulation/inhibition e)Water supply	a)Element supply b)Exposure d)Stimulation/inhibition	a)Exposure b)Stimulation/inhibition	a)Exposure b)Stimulation/inhibition	a)Exposure b)Stimulation/inhibition	a)Exposure b)Stimulation/inhibition c)Water supply	a) Export
4	b)Convection	a)Deposition b)Relocation c)Resuspension d)Saturation e)Sorption/desorption	a) Convection	**Surface water** *Geometry *Material composition *RN inventory *Stage of succession *Temperature*Water composition	a)Covering b)Phase transition	a)Element supply b)Exposure c)Habitat supply d)light-related processes f)Stimulation/inhibition g)Water supply	a)Element supply b)Exposure d)Habitat supply f)Stimulation/inhibition	b)Exposure c)Food supply d)Habitat supply f)Stimulation/inhibition	a)Element supply b)Exposure c)Habitat supply e)Stimulation/inhibition	a)Element supply b)Exposure c)Habitat supply e)Stimulation/inhibition	a)Exposure b)Habitat supply c)Stimulation/inhibition d)Water supply	a)Export
5			a)Convection	a)Convection b)Deposition c)Phase transitions d)Wind stress	**Local atmosphere** *Geometry *Material composition *RN inventory *Stage of succession *Temperature*Water composition	a)Element supply b)Exposure d)Stimulation/inhibition	b)Exposure c)Stimulation/inhibition	b)Exposure	b)Exposure c)Stimulation/inhibition	b)Exposure c)Stimulation/inhibition	c)Exposure d)Stimulation/inhibition	a)Export
6		a)Bioturbation c)Death	b)Excretion e)Sorption/desorption f)Uptake	d)Death e)Excretion f)Interception j)Sorption/desorption k)Uptake	a)Acceleration c)Excretion g)Sorption/desorption h)Uptake	**Primary producers** *Geometry *Material composition *RN inventory *Stage of succession *Temperature*Water composition		a)Food supply	a)Food supply		a)Food supply b)Material supply	a)Export
7		a)Bioturbation b)Consumption d)Death e)Decomposition f)Excretion	c)Excretion f)Sorption/desorption g)Uptake	b)Consumption c)Death d)Decomposition e)Excretion j)Sorption/desorption k)Uptake	a)Excretion e)Sorption/desorption f)Uptake		**Decomposers** *Geometry *Material composition *RN inventory *Stage of succession *Temperature*Water composition	a) Food supply		a)Food supply	a)Food supply	
8		c)Death f)Sorption/desorption	b)Excretion e)Sorption/desorption	b)Consumption c)Death d)Excretion g)Particle release/trapping h)Sorption/desorption i)Uptake		a)Consumption	a)Consumption	**Filter feeders** *Geometry *Material composition *RN inventory *Stage of succession *Temperature*Water composition		b)Food supply	a)Food supply	
9		c)Death d)Excretion g)Sorption/desorption h)Uptake	b)Excretion e)Sorption/desorption f)Uptake	b)Death c)Excretion h)Sorption/desorption i)Uptake	a)Excretion e)Sorption/desorption f)Uptake	a)Consumption			**Herbivores** *Geometry *Material composition *RN inventory *Stage of succession *Temperature*Water composition	a)Food supply	a)Food supply	
10		d)Excretion g)Sorption/desorption h)Uptake	b)Excretion e)Sorption/desorption f)Uptake	b)Excretion g)Sorption/desorption h)Uptake	a)Excretion e)Sorption/desorption f)Uptake		a)Consumption	a)Consumption	a)Consumption	**Carnivores** *Geometry *Material composition *RN inventory *Stage of succession *Temperature*Water composition	b)Food supply	
11	a)Intrusion	a)Anthropogenic release b)Consolidation g)Material use h)Relocation	a)Anthropogenic release d)Uptake e)Water use	a)Acceleration b)Anthropogenic release i)Uptake j)Water use	b)Anthropogenic release c)Convection h)Uptake	a)Consumption d)Stimulation/inhibition	c)Species introduction/extermination		a)Consumption c)Species introduction/extermination d)Stimulation/inhibition	d)Species introduction/extermination	**Humans** *Geometry *Material composition *RN inventory	
12	a)Change in rock surface location	a)Change in rock surface location b)Import c)light-related processes	a) Import b)light-related processes c)Saturation	a)Convections b)Import c)light-related processes d)Sea-level change	a)Import b)light-related processes	a)Import b)light-related processes c)Stimulation/inhibition	a)Import b)Stimulation/inhibition	a)Import b)Stimulation/inhibition	a)Import b)Stimulation/inhibition	a)Import b)Stimulation/inhibition	b)Stimulation/inhibition	**External conditions**

Appendix C

Features influence on processes

In SKBs database features are also named variables. In table beow, features are therefore named variables in roder to be consistence with the database structure. SKB's FEP databse includes the thehandling of processes in different safety assessments.

Bio01 Bioturbation

Variable	Variable influence on process		Process influence on variable	
	Influence present? Yes/No	Description Comment	Influence present? Yes/No	Description Comment
Geometry	No	There is no direct effect of geometry on bioturbation.	Yes	The depth of the to layer in both aquatic and terrestial/agricultural laysers are defined by the bioturation depth.
Material composition	Yes	Matrial composition can stimulate or inhibit bioturbation.	Yes	Bioturbation may alter the composition and structure of regolith.
Radionuclide Inventory	No	The expected concentrations of radionuclides are too small to influence the bioturbation.	Yes	Bioturbation is assumed to affect the radionuclide inventory by mixing of the upper regolith layer.
Stage of succession	Yes	Type of ecosystem determines the depth of the bioturbated layer, i.e. bioturbation reaches different depths depending on the type of ecosystem.	Yes	Drainage of a mire and subsequent ploughing will make it possible for bioturbating organisms to invade the unsaturated zone. This will increase the mineralisation and cause a long-term lowering of the organic content.
Temperature	Yes	Temperature affect the acitivity of biota and thus affects bioturbation. At low temperatures activity decreases and activity rises as temperature gets higher up to a certain point above which activity again may decrease.	Yes	Biota may theoretically affect temperature by their metabolic heat. Other factors have larger effects on temperature in ecosystems and this influence is insignificant.
Water composition	Yes	The water composition can stimulate or inhibit bioturbation.	Yes	Bioturbation may alter the composition of water in the regolith.

Bio02 Consumption

Variable	Variable influence on process		Process influence on variable	
	Influence present? Yes/No	Description Comment	Influence present? Yes/No	Description Comment
Geometry	No	Geometry indirectly affects consumption, e.g. fish and crayfish needs a certain water depth to survive winters with decreasing oxygen availability below ice. However, that influence is indirect and goes via habitat supply and amounts of different biosphere compartments.	Yes	Consumption can affect the geometry by decreasing the amounts of a component.
Material composition	Yes	Material composition of regolith and particulate matter in water affect the consumption rate by decomposers. In addition, only regolith suitable for agriculture is used for growing edible items.	Yes	Consumption can affect material composition, e.g. decomposers may affect the organic content of regolith.
Radionuclide inventory	No	The expected concentrations of radionuclides are too small to influence the consumption.	Yes	Consumption relocates radionuclides from the food source to the consumers.
Stage of succession	Yes	Stage of succession affects what and how much is consumed.	Yes	Consumption may affect the successional dynamics but is in this context assumed not to have any significant affect on the succession of the ecosystems of main interest for the safety assessment.
Temperature	Yes	Temperature affects the acitivity of biota, and thus affects the rate of consumption.	Yes	Biota may theoretically affect temperature by their metabolic heat. Other factors have larger effects on temperature in ecosystems and this influence is insignificant.
Water composition	Yes	The composition of water such as amount of organic carbon may stimulate or inhibit consumption by decomposers.	Yes	Decomposers may affect the amount of organic matter in water by consuming the easily degradable low molecular compounds.

Bio03 Death

Variable	Variable influence on process		Process influence on variable	
	Influence present? Yes/No	Description Comment	Influence present? Yes/No	Description Comment
Geometry	No	There is no direct influence of geometry on the death rate of organisms.	Yes	Large amounts of e.g. litter fall may increase the regolith depth.
Material composition	No	There is no direct effect of material composition on the death rate of organisms.	Yes	Dead organic matter might generate a higher organic content in the regolith and surface waters.
Radionuclide Inventory	No	The expected concentrations of radionuclides are too small to influence the death.	Yes	Death transfers radionuclides from biota to the organic matter in regolith or water and thus redistributes the radionuclide inventory in ecosystems.
Stage of succession	Yes	The type of ecosystem affects the type of biota and thus also amount of dead organic matter that is produced.	Yes	Death generates organic matter that affects terrestrialisation, i.e. the succession from one ecosystem to another.
Temperature	Yes	The temperature affects rates of production and death.	No	There is no effect on temperature by death.
Water composition	Yes	In extreme conditions such as chemiacal releases of toxins, water chemistry could affect the death of organisms, However, for normal conditions, water chemistry does not affect the death rates of organisms.	Yes	Death affects the water composition by affecting the amount of dead organic matter in the water.

Bio04 Decomposition

Variable	Variable influence on process		Process influence on variable	
	Influence present? Yes/No	Description Comment	Influence present? Yes/No	Description Comment
Geometry	No	Decomposition may occur as long as there are available organic matter to decompose regardless of the depth of regolith or water.	Yes	By decomposition, particulate organic matter can be transformed to dissolved elements and decomposition can thereby affect the geometry by decreasing the depths of the regolith layers.
Material composition	Yes	Material composition influences decomposition since the concentration of organic matter affects the speed of decomposition.	Yes	Decomposition of organic matter affects the material composistion of the regolith.
Radionuclide Inventory	No	The expected concentrations of radionuclides are too small to influence the decomposition.	Yes	Decomposition may affect the radionuclide inventory of different biosphere components by e.g. release of radionuclides in organic compounds and following flux from regolith to other compartments.
Stage of succession	Yes	Ecosystem type affects the rate of decomposition.	Yes	Decomposition affects the amount of organic matter that remains in regolith and contributes to the build up of organic matter. This affects terrestrialisation, i.e. the succession from one ecosystem to another.
Temperature	Yes	Temperature affects the acitivity of biota, and thus affects decomposition rate.	Yes	Biota may theoretically affect temperature by their metabolic heat. Other factors have larger effects on temperature in ecosystems.
Water composition	Yes	High amount of organic matter generates a high decomposition rate.	Yes	Decomposition affects the amount of organic matter in the water.

Bio05 Excretion

Variable	Variable influence on process		Process influence on variable	
	Influence present? Yes/No	**Description Comment**	**Influence present? Yes/No**	**Description Comment**
Geometry	No	There is no direct effect on excretion rate by the geometry of the ecosystem components.	No	There is no direct effect on geometry by the excretion of organisms.
Material composition	Yes	pH and salinity may stress organisms to increase excretion. However, during the normal variations in natural ecosystems that are assumed to occur material composition is assumed not to alter the excretion rates of organisms.	Yes	Excretion of elements may affect the compostion of elements in regolith and water.
Radionuclide inventory	No	The expected concentrations of radionuclides are too small to influence the excreation.	Yes	Excretion transfers radionuclides from biota to regolith, water or air and thus redistributes the radionuclide inventory in ecosystems.
Stage of succession	Yes	The type of ecosystem may affect the excretion rate of biota.	No	There is no direct effect of excretion on stage of succession.
Temperature	Yes	Temperature affect the acitivity of biota, and thus may affect excretion rate.	Yes	Biota may theoretically affect temperature by their metabolic heat. Other factors have higher effects on temperature in ecosystems and this influence is considered insignificant.
Water composition	Yes	pH and salinity may stress organisms to increase the excretion. However, during the normal variations in natural ecosystems that are assumed to occur, water composition is assumed not to alter the excretion rates of organisms.	Yes	Excretion of elements may affect the composition of elements in water and regolith.

Bio06 Food supply

Variable	Variable influence on process		Process influence on variable	
	Influence present? Yes/No	Description Comment	Influence present? Yes/No	Description Comment
Geometry	Yes	Geometry of the abiotic components affects the amounts of biota that can live there and thus the available food supply. Geometry of organisms also influences whether they can be consumed by others, e.g. size of the prey must be able to be handled by the consumer.	No	There is no direct effect on geometry by food supply.
Material composition	Yes	Material composition of regolith/soils affects species and yield of edible food.	No	There is no direct effect on material composition by food supply.
Radionuclide Inventory	No	The expected concentrations of radionuclides are too small to influence the food supply.	No	When the food is consumed (process consumption) there is a flux of radionuclides between biosphere components, but there is no effect on radionuclide inventory by food supply.
Stage of succession	Yes	Different types of ecosystem generate different types of food supply.	No	There is no direct effect on stage of succession by food supply.
Temperature	Yes	Temperature affects growth rate, yield of biota and available species and thus affects the amount of available food.	Yes	Biota may theoretically affect temperature by their metabolic heat. The metabolic heat of a large food supply of biota may thus theoretically influence the temperature. Other factors have larger effects on temperature in ecosystems and this influence is assumed to be insignificant.
Water composition	Yes	Water composition affects growth rate, yield of biota, and species composition and these in turn affect the amount of avaiable food.	No	There is no direct effect on water composition by food supply.

Bio07 Growth

Variable	Variable influence on process		Process influence on variable	
	Influence present? Yes/No	**Description Comment**	**Influence present? Yes/No**	**Description Comment**
Geometry	Yes	Geometry affects growth by setting environmental constraints, e.g. photic depths are dependent on the geometry of aquatic basins.	Yes	Growth may affect the geometry of ecosystem components, e.g. growth of large colonies of filter feeders may affect the geometry of aquatic bottoms, the growth of trees affects the geometry of forests.
Material composition	Yes	Nutrient concentrations, pH, salinity etc affect the growth rates.	No	Growth only indirectly affects the material composition (by the process uptake of elements) but there is no direct influence of growth on material composition.
Radionuclide inventory	No	The expected concentrations of radionuclides are too small to influence growth.	Yes	Rapid growth rate may dilute the radionuclide inventory in organisms.
Stage of succession	Yes	Stage of succession affects the type of ecosystem and thereby species composition. Different species have different growth rates.	Yes	Growth can influence stage of succession, e.g. reed production leads to ingrowth and terrestrialisation of marine basins and lakes.
Temperature	Yes	Temperature affects the growth rate of organisms.	Yes	Biota may theoretically affect temperature by their metabolic heat. T. Other factors have larger effects on temperature in ecosystems.
Water composition	Yes	Nutrient concentrations, pH, salinity etc affect growth rates.	No	Growth only indirectly affects the water composition (by the process uptake of elements) and there is no direct effect of growth on water composition.

Bio08 Habitat supply

Variable	Variable influence on process		Process influence on variable	
	Influence present? Yes/No	Description Comment	Influence present? Yes/No	Description Comment
Geometry	Yes	Depths and volumes directly affect the habitats available to biota and thereby the species distribution and abundance.	Yes	The thickness of the uper regolith layer sets the limits to oxidized habitat in the mire and the aquatic ecosystems.
Material composition	Yes	Material composition affects habitat supply by providing suitable habitats (porosity, pH) for various biota.	No	There is no direct effect on material composition by habitat supply.
Radionuclide inventory	No	The expected concentrations of radionuclides are too small to influence the habitat supply.	No	Habitat supply inderectly affects radionuclide inventory by determining the type of biota in the biosphere and thus the distribution of radionuclides within the biosphere. However, it is by uptake or convection the radionuclides are redistributed, not by the availability of potential habitats.
Stage of succession	Yes	Stage of succession determines the availble habitats for biota.	No	There is no direct effect on stage of succession by habitat supply.
Temperature	Yes	Biota have different temerature optima and temperature can influence e.g. whether an ecosystem can be utlisied as a habitat.	No	There is no direct effect on temperature by habitat supply.
Water composition	Yes	Water composition affects habitat supply by providing suitable habitats (salinity, pH) for various biota.	No	There is no effect on water composition by the habitat supply.

Bio09 Intrusion

Variable	Variable influence on process		Process influence on variable	
	Influence present? Yes/No	**Description Comment**	**Influence present? Yes/No**	**Description Comment**
Geometry	Yes	Geometry affects the potential for intrusion, i.e. the potential for intrusion is lower at very large depths compared with shallow depths.	Yes	Intrusion may alter the geometry of the landscape.
Material composition	Yes	Composition of the regolith may affect the possibilty for intrusion.	Yes	The material composition may be affected by excavating activities in the regolith.
Radionuclide inventory	Yes	The radionuclide inventory can potentially influence the intrusion if the radionuclide inventory is of interest for humans.	Yes	Intrusion may cause a release and subsequent transfer of radionuclides to the surface.
Stage of succession	Yes	Stage of succession influences intrusion, since intrusion is more or less likely depending on ecosystem type, i.e. drilling into the repository is much more likely when the repository is situated below a terrestrial area than below the sea bed.	No	There is no direct effect on stage of succession by intrusion.
Temperature	Yes	Temperature may affect the potential for intrusion, e.g.intrusion into a repository is not likely during permafrost or glacial conditions.	Yes	Intrusion may affect the temperature of the surface system if radionuclides are brought to the surface.
Water composition	No	There is no direct effect of water composition on the potential for intrusion.	No	Water composition may be indirectly affected by intrusion, but this interaction goes via the process convection and there is no direct effect of intrusion on water composition in the biosphere.

Bio10 Material supply

Variable	Variable influence on process		Process influence on variable	
	Influence present? Yes/No	Description Comment	Influence present? Yes/No	Description Comment
Geometry	Yes	Geometry may influence the amount of material supply, e.g. peat depth influences the amounts of biomass fuel.	Yes	There are few direct effects on geometry by material supply. It is only when the material is used that there is an effect (treated in the process material use). However, the potential use has been an important factor to structure human settlements.
Material composition	Yes	Regolith may be suitable for different purposes depending on composition.	No	There is no effect on material composition by material supply.
Radionuclide inventory	No	The expected concentrations of radionuclides are too small to to be immediately recognized and therefore affect whether something is to be used as material.	No	There is no direct effect on radionuclide inventory by material supply. It is only when the material is used that there is an effect (treated in the process material use).
Stage of succession	Yes	Type of ecosystem determines the available materials to be used.	No	There is no direct effect on stage of succession by material supply.
Temperature	Yes	Various temperatures can affect what type of biota are present and whether regolith are frozen or not which in turn affects whether it can be used as material.	No	There is no direct effect on temperature by material supply.
Water composition	No	There is no direct effect of water composition on material supply.	No	There is no direct effect on water composition by material supply.

Bio12 Particle release/trapping

Variable	Variable influence on process		Process influence on variable	
	Influence present? Yes/No	Description Comment	Influence present? Yes/No	Description Comment
Geometry	Yes	Geometry may affect the amouts of particles trapped on an organism but the main particle trapping is active (e.g. by filter feeders) and the geometry is of minor importance.	No	There is no direct effect on geometry by particle release or trapping. Potentially, particle release or trapping can change the amount of matter that is deposited and contributes to regolith depths (i.e. geometry) but this goes via the process deposition.
Material composition	No	Since particle trapping is generally a non-selective process (i.e. organisms filter without selection) there is no direct effect of material composition on particle release/trapping	Yes	Since particle Selective particle trapping may have an effect on material composition. However, since particle trapping is generally a non-selective process, the effect on material composition is considered insignificant.
Radionuclide inventory	No	The expected concentrations of radionuclides are too small to influence the particle/release trapping.	Yes	Particle release and trapping affects the dristributionof radionuclides between abiotic and biotic compontents and thereby affects the radionuclide inventory.
Stage of succession	Yes	The type of ecosystem determines the rate of particle release or trapping and from which media particles are trapped (water/air).	No	There is no direct effect of particle release trapping on stage of succession. Indirectly particle trapping may decrease sediment accumulation and decrease terrestrialisaion, but this goes via an influence on the process deposition.
Temperature	No	Climate influences biota and may affect the timing and amounts of particles, e.g. a warmer climate may lead to higher amounts of pollen and earlier release. However, the effects are assumed to be limited in temporal and spatial scale and not have a large influence on the amounts of particles in atmosphere or water on an annual scale.	No	There is no direct effect on temperature by particle release/trapping.
Water composition	Yes	The amounts of particulate matter will affect the rate of trapping by filter feeders.	Yes	Particle release/trapping affects the water composition by removing or releasing particles into the water.

Bio13 Primary production

Variable	Variable influence on process		Process influence on variable	
	Influence present? Yes/No	**Description Comment**	**Influence present? Yes/No**	**Description Comment**
Geometry	Yes	Geometry affects primary production by affecting depth of water basins (i.e. is the benthic habitat photic), shading by hills etc.	Yes	Primary production does not directly influence the geometry of ecossytems, but if primary production leads to an increase in biomass the geometry may be altered; this is handled through the process growth.
Material composition	Yes	Primary producers may be limited by the composition of the regolith e.g. by nutrient limitation, or other unfavourable conditions for roots.	Yes	Primary producers may affect the material composition by using elements and depleting the soils/sediments. However, as a conservative assumption, the system is assumed to always be suitable for priamary producers.
Radionuclide Inventory	No	The expected concentrations of radionuclides are too small to influence the primary production	Yes	Primary production influences the radionuclide inventory by a flux of radionuclides from abiotic components into biota.
Stage of succession	Yes	The type of ecosystem determines species of primary producers and rates of primary production.	Yes	Primary production contributes to terrestrialisation. Primary production may lead to growth of primary producers and to organic matter settling on the sediments and thereby lead to ingrowth and terrestrialisation.
Temperature	Yes	Temperature affects primary production. Nutrients, light, and water are commonly more important for primary production variations in temperature. However, with large temperature changes, temperature may have a substantial effect on primary production.	No	There is no direct effect of primary production on temperature.
Water composition	Yes	Primary production may be affected by nutrient concentrations and pH.	Yes	Primary production may affect the water compostion by using elements from the water.

Bio14 Stimulation/Inhibition

Variable	Variable influence on process		Process influence on variable	
	Influence present? Yes/No	**Description Comment**	**Influence present? Yes/No**	**Description Comment**
Geometry	Yes	Components may stimulate /inhibit each other by their geometry.	Yes	Stimulatio/inhibition of organisms may affect the amount of the organisms.
Material composition	Yes	Components may stimulate /inhibit each other by their material composition.	No	There is no direct effect of stimulation/inhibition on material composition.
Radionuclide inventory	No	The expected concentrations of radionuclides are too small to influence stimulation/inhibition.	No	There is no direct effect of stimulation/inhibition on radionuclide inventory. Stimulation/inhibition can affect the presence of species and thereby affect the distribution of radionuclides, but the influence is indirect and the distribution of radionuclides is determined via uptake, production etc.
Stage of succession	Yes	Stage of succession affects the stage of the ecosystem and thereby what stimulation and inhibition may occur.	No	There is no direct effect of stimulation/inhibition on stage of succession.
Temperature	Yes	The temperature of abiotic components may stimulate or inhibit biotic components.	No	There is no direct effect of stimulation/inhibition on temperature.
Water composition	Yes	Abiotic components may stimulate or inhibit biotic components by distinctions in water composition.	No	There is no direct effect of stimulation/inhibition on water composition.

Bio15 Uptake

Variable	Variable influence on process		Process influence on variable	
	Influence present? Yes/No	Description Comment	Influence present? Yes/No	Description Comment
Geometry	Yes	The geometry of the vegetation affects uptake rates.	No	Uptake by organisms is too small to have an effect on the geometry of ecosystem components.
Material composition	Yes	Material composition determines possible uptake.	Yes	Hyper-accumulating plants may alter the material composition by selective uptake.
Radionuclide Inventory	No	The expected concentrations of radionuclides are too small to influence the uptake.	Yes	Uptake relocates radionuclides from abiotic components to biotic components.
Stage of succession	Yes	Ecosystem type determines organisms and thereby uptake.	No	There is no effect of uptake on stage of succession.
Temperature	Yes	Temperature affects the acitivity of biota, and thus affects uptake.	Yes	Biota may hypothetically affect temperature by their metabolic heat. Other factors have larger effects on temperature in ecosystems.
Water composition	Yes	Water composition can influence uptake rate from water.	Yes	Uptake may have an effect on water composition.

Bio16 Anthropogenic release

Variable	Variable influence on process		Process influence on variable	
	Influence present? Yes/No	**Description Comment**	**Influence present? Yes/No**	**Description Comment**
Geometry	Yes	Geometry may have an inluence on where humans release substances, e.g. it is unlikely that large industries are put on the top of mountains.	Yes	The geometry may be altered due to anthropogenic release, e.g. deposits of large quantities of matter.
Material composition	No	Humans are assumed to be able to release substances regardless of the material composition.	Yes	Human releases may affetc material composition.
Radionuclide Inventory	No	Humans are assumed to be able to release substances regardless of the radionuclide inventory.	Yes	Release of radionuclides may increase the radionuclide inventory, but this is not part of the safety assessment and only non radioactive release is considered in anthropogenic release. Large releases of other substances may dilute the radionuclide inventory, but this does not need to be considered since it would decrease dose.
Stage of succession	No	Humans are assumed to be able to release substances regardless of the stage of succession.	Yes	Humans may affect stage of succession, e.g. by filling in a bay or a lake which may then speed up succession.
Temperature	No	Humans are assumed to be able to release substances regardless of the temperature.	Yes	Anthropogenic release may affect temperature, e.g. the release of cooling water increase the water temperature in aquatic ecosystems.
Water composition	No	Humans are assumed to be able to release substances regardless of the water composition.	Yes	Anthropogenic releases may affect water composition.

Bio17 Material use

Variable	Variable influence on process		Process influence on variable	
	Influence present? Yes/No	**Description Comment**	**Influence present? Yes/No**	**Description Comment**
Geometry	Yes	Geometry can affect the amount of material that is avaiable for material use, e.g. peat depth.	Yes	Material use may have a large effect on the geometry, e.g. if all peat is extracted from a wetland to be used for fuel.
Material composition	Yes	Material composition affects the potential for the material to be used, e.g. peat may be utlisied for fuel whereas top soil may not.	Yes	Material use may affect the material composition. No direct effects of material use on material composition are considered, i.e. the material is assumed to be removed completely and no selective use of only certain substances is assumed to occur.
Radionuclide Inventory	No	The expected concentrations of radionuclides are too small to influence the material use.	Yes	Material use may cause relocation of radionuclides from one component to another e.g. from burning peat to atmosphere.
Stage of succession	Yes	Type of ecosystem determines potential material use and different materials can be used from the different ecosystems.	Yes	Material use can alter the stage of succession, e.g. if reed is removed from lakes the timing of terrestrialisation is delayed, if woods are cut down to create farmland the succession to agricultural land takes place.
Temperature	Yes	Low temperatures may inhibit the possibilities for material use, e.g. there are no trees and no peat formation during periglacial climate.	No	There is no direct effect on temperature by material use. If peat is used as fossil fuel, of course temperatures are increased in the intermediate vicinity of burning. However, the effect on temperature in the ecosystems are assumed to be insignificant.
Water composition	No	There is no direct effect of water composition on material use. Water composition can affect the use of water by humans but this interaction goes via the process water use.	No	There is no direct effect on water composition by material use. Of course material use arising frommining etc could release toxic substances to the surrounding aquatic environment, but this interaction goes via the process anthropogenic release.

Bio18 Species introduction/extermination

Variable	Variable influence on process Influence present? Yes/No	 Description Comment	Process influence on variable Influence present? Yes/No	 Description Comment
Geometry	Yes	Geometry (depth of water and soil layers etc) may delimit the potential distribution of species and possibility for introduction or extinction of species.	Yes	Athough it is possible that introduction of some species, e.g. filter feeders may affect the bottom topography, the effect on geometry is assumed to be insignificant. Extermination of species could have an affect on the geometry if large species were exterminated (like pine or reed). However, it is very unlikely that large common primary producers would be exterminated and it is not considered necessary to address this.
Material composition	Yes	The chemical composition of a material may determine if a habitat is suitable for a specific species.	No	Species introduction/extermination may influence the material composition indirectly, e.g. depleting the soils in certain nutrients goes via the process uptake, or causing increased mixing depth goes via bioturbation, and there is no direct influence of species introduction/extermination on material composition.
Radionuclide Inventory	No	The expected concentrations of radionuclides are too small to influence species introduction/extermination.	Yes	Introduction of species may lead to a redistribution of radionuclides in the ecosystem.
Stage of succession	Yes	The stage of succession may determine if a habitat is suitable for a specific species.	No	There is no direct effect of species introduction/extermination on stage of succession. If reed were exterminated it could delay succession but it is very unlikely that humans would exterminate reed and it is not considered necessary to address this.
Temperature	Yes	Temperature may determine if a habitat is suitable for a specific species, i.e. if introduction is possible.	Yes	Species extermination may have an effect on temperature, e.g. deforestation can affect the soil temperature. However, for the modeling of natural ecosystems, this effect of species introduction and extermination is assumed to be insignificant and present temperature conditions are assumed to prevail.
Water composition	Yes	Water composition may determine if a habitat is suitable for a specific species.	No	There is no direct effect on water composition by species introduction or extermination. Indirect effects occur, e.g. organisms may affect the chemical composition by taking up and excreting specific elements (processes uptake an excretion).

Bio19 Water use

Variable	Variable influence on process		Process influence on variable	
	Influence present? Yes/No	**Description Comment**	**Influence present? Yes/No**	**Description Comment**
Geometry	Yes	The geometry affects the water supply, i.e. the amount of water that is available. There is no direct effect of geometry on the amount of water that humans need. However, geometry affects the source of water, If surface water is available it may be used, otherwise humans may utlise water in regolith or water in geosphere from wells.	Yes	Very large water use, e.g energy production, cooling water etc, may affect the geometry by affecting the water volumes present.
Material composition	No	There is no effect of material composition on water use.	No	There is no effect of water use on material composition.
Radionuclide Inventory	No	The expected concentrations of radionuclides are too small to influence wateruse.	Yes	Water use relocates radionuclides in water from one place (e.g. lake) to another (e.g. agricultural land by irrigation).
Stage of succession	Yes	Stage of succession determines whether fresh water sources are available, e.g. wells are not drilled when an area is situated below the sea.	No	There is no direct effect of water use on stage of succession.
Temperature	Yes	Temperature affects water use, i.e. wells are not drilled in periglacial landscapes where the ground is frozen.	No	There is no direct effect of water use on temperature.
Water composition	Yes	Water composition affects the potential for various uses of the water, e.g. saline water is not suitable for irrigation.	Yes	Potentially, water could be filtered before use, thus altering the water composition in the remaining water source. However, this effect is assumed to be insignificant and is not considered to be an influence.

Bio 21 Consolidation

Variable	Variable influence on process		Process influence on variable	
	Influence present? Yes/No	**Description Comment**	**Influence present? Yes/No**	**Description Comment**
Geometry	Yes	The geometry may affect consolidation, and a thicker regolith gives a higher load and therby increased consolidation.	Yes	Consolidation may, when the load expels pore water and pore air, decreases the regolith volume.
Material composition	Yes	Different materials may be prone to consolidation to various degrees.	No	There is no direct effect of consolidation on material composion.
Radionuclide Inventory	No	There is no direct effect of radionuclide inventory on consolidation.	Yes	As a consequence of consolidation, radionuclide-contaminated air or water may be transported out of the regolith layer together with water thereby affecting the radionuclide inventory.
Stage of succesion	No	The type of ecosystem does not directly influence consolidation.	No	There is no direct effect of consolidation on stage of succesion.
Temperature	No	There is no direct effect of temperature on consolidation except during an ice age when an ice sheet may contribute to consolidation, This is treated in the process loading.	No	There is no direct effect of consolidation on temperature.
Water composition	No	There is no direct effect of water composition on consolidation.	Yes	As a consequence of consolidation, dissolved elements in air or water may be transported out of the regolith layer together with the water thereby affecting the water composition.

Bio22 Element supply

Variable	Variable influence on process		Process influence on variable	
	Influence present? Yes/No	**Description Comment**	**Influence present? Yes/No**	**Description Comment**
Geometry	Yes	The volumes of the ecosystem media determine the amounts of elements.	No	There is no direct effect of element supply on the geometry of the ecosystem component.
Material composition	Yes	Material composition incldues the elemental composition of the regolith and thus influences the amounts of available elements.	No	There is no effect of element supply on material compsition. The material composition is only changed after supply has actually been used, but that is handled in the processes uptake and consumption.
Radionuclide inventory	Yes	Determines the radionuclide pool available for transfer and accumulation in the landscape.	Yes	Element supply is important for the transfer of radionuclides between compartments since a large element supply may dilute the radionuclides and lead to lower radionuclide uptake whereas a low element supply may concentrate the radionuclides and lead to a high uptake of radionuclides.
Stage of succession	No	There is no direct influence of element supply on stage of succession, because the influence goes via geometry.	No	There is no effect of element supply on stage of succession.
Temperature	Yes	The temperature may alter the availability of elements eg by freezing.	No	There is no effect of element supply on temperature.
Water composition	Yes	Water composition includes water chemistry and thus the amounts of available elements for biota and humans.	No	There is no effect of element supply on water composition. The water composition is only changed after supply has actually been used, but that is handled in the processes uptake and consumption.

Bio24 Phase transition

Variable	Variable influence on process		Process influence on variable	
	Influence present? Yes/No	**Description Comment**	**Influence present? Yes/No**	**Description Comment**
Geometry	Yes	The geometry of water influences the amount of evaporation (i.e. a phase transition of water), e.g. the evaporation from a large shallow lake is higher than from a small but deep lake.	Yes	There is a limited effect of phase transitions on geometry. At high evaporation rates, lake levels and sea levels may be lowered. Evaporation is important for water balances.
Material composition	Yes	Material composition may have an effect on the dissolution of elements from solid to liquid/gaseous pase.	Yes	Phase transitions affect the material composition by the transfer of elements between solid, liquid and gaseous phases.
Radionuclide inventory	No	Radionuclide inventory does not affect phase transitions in ecosystems. The radionuclides may themselves be part of phase transitions but then the influence is from the process on the inventory.	Yes	For reactive radionuclides, phase transition may cause relocation of radionuclides.
Stage of succession	Yes	Stage of succession affects phase transitions, e.g. the evaporation rate is different on land and open water.	No	There is no direct effect of phase transitions on stage of succession.
Temperature	Yes	Temperature affects phase transitions, e.g. water turns to ice during winter.	Yes	Phase transition may affect the temperature, but is considered to be insignificant in comparison to other interactions.
Water composition	Yes	Water composition may have an effect on phase transitions, e.g. salt water freeeze at a different temperature from fresh water.	Yes	Phase transitions may affect the composition of water, e.g. due to dissolution of elements from solid to liquid form.

Bio25 Physical properties change

Variable	Variable influence on process		Process influence on variable	
	Influence present? Yes/No	**Description Comment**	**Influence present? Yes/No**	**Description Comment**
Geometry	Yes	The water pressure affects the density of water in regolith and thereby geometry (depths and thereby pressure) may influence physical properties change.	Yes	Physical properties change may affect the geometry, e.g changes in salinity may lead to increased or decreased volume, this change is assumed to be small.
Material composition	No	There is no direct effect of material composition on physical properties change.	No	Physical properties change is, in the SKB definition, limited to changes in volume, density and/or viscosity of water and there is no direct effect on material composition.
Radionuclide Inventory	No	There is no direct effect of the radionuclide inventory on physical properties change.	No	There is no direct effect of physical properties change on the radionuclide inventory, although the inventory may be affected indirectly by altered flow (convection).
Stage of succession	Yes	Physical properties change occurs in water and thus the type of ecosystem and amounts of available water affects whether physical properties change occurs.	Yes	Water volume is dependent on density, which is one of the reasons for sea level rise due to global warming. An increased sea level rise may affect timing of transformation from marine to limnic stage, i.e. affecting stage of succession.
Temperature	Yes	Temperature has a strong effect on the density of water.	No	There is no direct effect of physcial properties change on temperature.
Water composition	Yes	Water composition may affect changes in volume and density. The density and viscosity of water is the driving force for the turnover of water.	Yes	The water pressure affects the density of water in regolith and thereby affects water composition change.

Bio26 Reactions

Variable	Variable influence on process		Process influence on variable	
	Influence present? Yes/No	Description Comment	Influence present? Yes/No	Description Comment
Geometry	No	There is no direct effect of geometry on reactions.	No	There is no direct effect on geometry by reactions.
Material composition	Yes	Reactions can be dependent on material composition, e.g. concentrations of elements.	Yes	Reactions can affect material composition.
Radionuclide inventory	No	The expected concentrations of radionuclides are too small to influence the reactions.	Yes	Reactions may cause fluxes of radionuclides between biosphere components e.g. between water and atmosphere.
Stage of succession	No	There is no direct effect of stage of succession on reactions.	No	There is no direct effect of reactions on stage of succession.
Temperature	Yes	Reaction includes reaction rate, which is affected by the temperature, i.e. temperature can affect the rate of reactions.	Yes	Reactions may cause temperature change.
Water composition	Yes	Reactions can be dependent on water composition, e.g. pH, salinity etc.	Yes	Reactions can affect water composition since new componds can be formed in reactions in water.

Bio27 Sorption/desorption

Variable	Variable influence on process Influence present? Yes/No	Description Comment	Process influence on variable Influence present? Yes/No	Description Comment
Geometry	Yes	The geometry affects the sorption/desorption, the larger the area, the larger potential for sorption.	No	There is no direct effect of sorption/desorption on geometry.
Material composition	Yes	The material composition is important for the sorption/desorption of elements.	Yes	Sorption/desorption can affect material composition.
Radionuclide inventory	Yes	The type of radionuclides may affect the sorption/desorption of elements. However, the expected concentrations of radionuclides are small and although the type of radionuclides affect the sorption of the radionuclide itself it is not assumed to affect sorption properties of the components in general.	Yes	Sorption / desorption may lead to a flux from one biosphere component to another.
Stage of succession	Yes	Stage of succession may affect sorption/desorption, e.g. chemistry differences between saline and fresh waters may lead to different Kd values.	No	There is no direct effect of sorption/desoprtion on stage of succession.
Temperature	Yes	Temperature may affect the affinity for particles. However, this effect is assumed to be insignifcant compared to the effects of particle densities, geometry, and composition.	No	There is no direct effect of sorption/desorption on temperature.
Water composition	Yes	The water composition is important for the sorption/desorption of elements.	Yes	Sorption/desorption can affect water composition.

Bio28 Water supply

Variable	Variable influence on process		Process influence on variable	
	Influence present? Yes/No	**Description Comment**	**Influence present? Yes/No**	**Description Comment**
Geometry	Yes	The landscape geometery determines the available water volumes, i.e. water supply.	No	There is no direct effect of water supply on geometry. Only when the water is used (water use), there may be an effect on the geometry, e.g. effect on water volumes.
Material composition	No	There is no direct effect of material composition on water supply.	No	There is no direct effect of water supply on material composition.
Radionuclide inventory	No	The expected concentra-tions of radionuclides are too small to influence water supply.	Yes	The water supply may deter-mine the concentration of radionucliides, i.e. a radionu-clide release to a small water supply with low yield will give higher concentrations than a radionuclide release to a water supply with high yield.
Stage of succession	Yes	Depending on stage of succession an eco-sysytem could be aquatic or terrestrial, i.e. have varying capacity for water supply.	No	There is no direct effect of water supply on stage of succession.
Temperature	Yes	Temperature effects the access to water, e.g. wells are typically not drilled in periglacial areas, limiting the water supply from regolith.	No	There is no effect of water supply on temperature.
Water composition	Yes	Depending on water com-position, the water migth be more or less suitable for uptake or drinking.	No	There is no direct effect of water supply on water composition. Theoretically water use can affect the water composition, but that is treated in the process water use.

Bio29 Weathering

Variable	Variable influence on process		Process influence on variable	
	Influence present? Yes/No	**Description Comment**	**Influence present? Yes/No**	**Description Comment**
Geometry	Yes	The geometry of the rego-lith and rock may affectthe rate of weathering.	Yes	Weathering may affect geom-etry by transforming solid rock and regolith to smaller pieces and transporting those pieces.
Material composition	Yes	Material composition can affect weathering.	Yes	Weathering affect material composition by affecting porosity, grain size etc.
Radionuclide inventory	No	There is no direct effect of radionuclide inventory on weathering.	Yes	Weathering may free naturally occuring radionuclides and release radionuclides adsorbed to eg mineral particles.
Stage of succession	Yes	By altering the ecosystem present and by altering the exposure to aquatic or terrestrial physical factors mediating weathering.	Yes	In long time perspectives, weathering affects stage of succession and may alter landscapes. However, in Forsmark, other processes (sea level change, change in rock surface location, and deposition) have a larger impact on the landscape.
Temperature	Yes	Temperature, through ground freezing, may induce weathering.	No	There is no direct effect of weathering on temperature.
Water composition	Yes	Water composition can affect weathering due to the chemical action of water, oxygen, carbon dioxide and organic acids.	Yes	Weathering can affect water composition by release of elements to the water.

Bio30 Wind stress

Variable	Variable influence on process		Process influence on variable	
	Influence present? Yes/No	**Description Comment**	**Influence present? Yes/No**	**Description Comment**
Geometry	Yes	Geometry affects wind stress. Differences in shore line location and topography change the wind shielding conditions.	Yes	Wind stress may cause variation in e.g. sea level.
Material composition	No	There is no direct effect of material composition on wind stress.	Yes	Although wind stress may lead to a change in material composition at the site of the deposit, the amount of sea spray in Forsmark is assumed to be very low and to have an insignificant effect on the material composition in terrestrial areas.
Radionuclide inventory	No	There is no direct effect of radionuclide inventory on wind stress.	Yes	Wind stress has an effect on wether water columns are mixed or not, thus it has a strong effect on the distribution of radionuclides in water. In addition radionuclides may be transfered from water to atmosphere via sea spray.
Stage of succession	Yes	Stage of succession affects wind stress by e.g canopy closure and thereby affecting the wind shielding conditions.	No	There is no direct effect of wind stress on stage of succession.
Temperature	No	There is no effect of temperature on wind stress.	Yes	Wind affects temperature.
Water composition	No	There is no direct effect of water composition on wind stress.	Yes	The water composition could theoretically be altered due to small amounts of water being blown away via sea spray. However, the magnitude of this process is insignificant and wind stress is assumed not to affect water composition.

Bio31 Acceleration

Variable	Variable influence on process		Process influence on variable	
	Influence present? Yes/No	Description Comment	Influence present? Yes/No	Description Comment
Geometry	Yes	Acceleration is influenced by components in the biosphere, such as topography.	No	There is no direct effect on geometry by acceleration.
Material composition	No	There is no direct effect of material composition on acceleration.	No	There is no direct effect of acceleration on material composition.
Radionuclide inventory	No	There is no direct effect of radionuclide inventory on acceleration.	Yes	The velocity of wind and water influences mixing and movement of the water column (convection) and can thereby influence the distribution on radionuclides.
Stage of succession	Yes	Acceleration is influenced by both biotic and abiotic components of the biosphere, such as topography, type and location of primary producers, man-made buildings etc.	No	There is no direct effect of acceleration on stage of succession.
Temperature	Yes	Temeprature can affect acceleration, e.g. low temepratures may slow down the acceleration by the higher viscosity of cold water.	No	There is no direct effect of acceleration on temperature. Indirectly, an increased wind speed affect convection which in turn affect temperature stratification in lakes which is caused (i.e. convection prevents stratification).
Water composition	Yes	The water composition may change the viscosity of water thereby affecting acceleration.	Yes	The acceleration affects the velocity of wind and water which in turn, influences the transport and mixing of the water column and can thereby affect water composition.

Bio32 Convection

Variable	Variable influence on process		Process influence on variable	
	Influence present? Yes/No	**Description Comment**	**Influence present? Yes/No**	**Description Comment**
Geometry	Yes	Fluxes of gases and water are affected by the topography and bathymetry.	No	Convection does not directly affect geometry. Convection of wind and water may lead to weathering or relocation but these aspects are treated in separate processes.
Material composition	Yes	Material composition may affect discharge and recharge.	No	Convection does not directly affect material composition, Convection may affect deposition and thereby material composition, but this is treated in the process deposition.
Radionuclide inventory	No	There is no direct effect of radionuclide inventory on convection.	Yes	Convection will contribute to the dispersion and fluxes of radionuclides in the biosphere system.
Stage of succession	Yes	The stage of succession will determine the type of ecosystem and thereby the media in which convection occurs.	No	There is no direct effect of convection on stage of succession.
Temperature	Yes	The temperature affects the viscosity of liquids as well as creating temperature stratification suppressing convection.	Yes	Mixing of e.g. water during convection will reduce temprature differences.
Water composition	Yes	The water composition may cause chemical stratification (e.g. salinity) inhibiting convection.	Yes	The convection of water will reduce concentration gradients.

Bio33 Covering

Variable	Variable influence on process		Process influence on variable	
	Influence present? Yes/No	Description Comment	Influence present? Yes/No	Description Comment
Geometry	Yes	Geometry may affect covering, e.g. large mountains are not covered to the same degree as flat areas. However, for the flat landscape of Forsmark, geometry has an insignificant effect on covering.	No	Covering has no effect on geometry. A thick ice sheet may depress regolith and affect the thickness of regolith, but this is treated in the process loading.
Material composition	No	Characteristics of the regolith, eg the porosity, affect establishment of primary producers, which may produce covering, but material composition does not directly result in cover of the regolith.	Yes	Covering may affect the material composition, if exchange with the atmosphere is prevented.
Radionuclide inventory	No	The expected concentrations of radionuclides are too small to influence covering.	Yes	Covering may affect the flux of radionuclides between different components in the system, e..g. preventing release from surface water to atmosphere when ice cover is present.
Stage of succession	Yes	Type of ecosystem affects covering.	Yes	Covering and stage of succession are associated with each other. Growth and thereby covering lead to terrestrialisation and influence the stage of succession.
Temperature	Yes	Temperature affects the occurence and duration of ice covers.	Yes	Covering affects the temperature, e.g. the cover may provide insolation and lead to large temperature differences.
Water composition	No	Water composition does not directly influence covering. Water composition may affect vegetation which makes up cover, but this is represented via primary producers. The salinity may also affect the freezing of water , but the salinity changes at Forsmark are too small to have a significant effect on the occurence of ice.	Yes	Covering affects water composition by inhibiting exchange between surface water and the atmosphere.

Bio34 Deposition

Variable	Variable influence on process		Process influence on variable	
	Influence present? Yes/No	Description Comment	Influence present? Yes/No	Description Comment
Geometry	Yes	The geometry affects deposition, precipitation is affected by topography and location in relation to mountains and sea, sedimentation is affected by water depths and currents.	Yes	Deposition can change the geometry.
Material composition	No	There is no direct effect of material composition on deposition.	Yes	Deposition on the surface of the regolith may alter the composition of the surface layers.
Radionuclide inventory	No	There is no direct effect of radionuclide inventory on deposition.	Yes	Deposition affects the flux of radionuclides to e.g. the sediment or regolith.
Stage of succession	Yes	Precipitation is similar over land and water. But sedimentation is affected by exposure and water depth that usually decreases during succession of aquatic ecosystems.	Yes	Deposition leads to terrestrialisation, i.e. transforms marine basins and lakes to terrestrial areas.
Temperature	Yes	Temperature determines the form of atmospheric deposition. In addition, climate affects the amount of precipitation.	No	There is no direct effect of deposition on temperature.
Water composition	Yes	Amounts of particles in water may affect the rate of sedimentation.	Yes	Deposition elements on the surface water may change the chemical properties.

Bio35 Export

Variable	Variable influence on process		Process influence on variable	
	Influence present? Yes/No	Description Comment	Influence present? Yes/No	Description Comment
Geometry	Yes	Volumes and geometries will affect the amount of material available for export out of the model domain.	Yes	Export may affect the geometry if substantial amounts are exported out of the site, e.g. due to landslide. Export of water and particles affect the amounts of water and particles in the biosphere object (withouth export amounts would increase).
Material composition	Yes	Material composition may affect export, e.g. the density and grain size may influence the likelyhood for export, due to resuspension.	Yes	Export may hypothetically influence the material composition if there is a selective export of some forms of matter. However, the main exports of material from ecosystems in Forsmark are of water and particles and no selective export is assumed to occur and influence material composition.
Radionuclide inventory	No	There is no direct effect of radionuclide inventory on export.	Yes	Export of radionuclides may affect the inventory in the modelled system.
Stage of succession	Yes	Type of ecosystem determines biota and material available for export.	Yes	Hypothetically, removal of sediment may change the stage of succession. Large long-term changes in such processes have not been considered. Emigration of all humans from a site may lead to forest ingrowth of agricultural land.
Temperature	Yes	Temeperature may affect the fluxes of media such as water and thereby the export.	Yes	There may be export of heat from a modelled system. However, the effect on both the exporting system and the recieving system are assumed to be insignificant.
Water composition	Yes	Water composition determines the amounts of elements and particles that are exported out of the model area.	Yes	Export may influence water composition if it is selective. However, export of water and elements is assumed to occur withouth altering the remaining composition.

Bio36 Import

Variable	Variable influence on process		Process influence on variable	
	Influence present? Yes/No	**Description Comment**	**Influence present? Yes/No**	**Description Comment**
Geometry	Yes	The geometry of the landscape affects the import to the modelled area.	Yes	Import of matter can influence the geometry, e.g. landslides. In the flat Forsmark area, import is not assumed to have a signficant influence on geometry.
Material composition	Yes	If the material composition is not suitable for agricultural purposes import of food from areas outside the model domain will incease.	Yes	Import may affect the material composition.
Radionuclide inventory	No	There is no direct effect of radionuclide inventory on import.	Yes	Import may affect the radionuclide inventory in the different biosphere components, e.g. due to dilution.
Stage of succession	Yes	The import may involve various transport pathways depending on stage of succession.	No	There is no direct effect of import on stage of succession.
Temperature	No	Large scale climate changes may affect precipitation patterns (considered for the process deposition), but otherwise there is no direct effect of temperature on import.	No	Import of abiotic components may affect the temperature in the model domain, but this effect is considered to be insignificant compared with large scale climate factors.
Water composition	Yes	A low quality of drinking water may trigger an import of drinking water.	Yes	Import may affect the chemical composition of water.

Bio37 Interception

Variable	Variable influence on process		Process influence on variable	
	Influence present? Yes/No	**Description Comment**	**Influence present? Yes/No**	**Description Comment**
Geometry	Yes	The geometry of vegetation influences the amount of deposition that is retained on it.	No	There is no effect of interception on the geometry of the biosphere components.
Material composition	No	There is no direct effect of material composition on interception. Material composition infuences the kind of vegetation present at a site which in turn affects interception, but this is not a direct influence but goes via primary producers and habitat supply.	Yes	Interception can influence the material composition by retaining some elements on the vegetation and the elements thereby do not reach the regolith.
Radionuclide inventory	No	There is no direct effect of radionuclide inventory on interception.	Yes	Interception may influence the radionuclide inventory in different biosphere components, e.g. if radionuclides are present in water that is used for irrigation.
Stage of succession	Yes	The stage of succession determines the type of vegetation and thereby the degree of interception.	No	There is no effect of interception on stage of succession.
Temperature	No	There is no direct effect of temperature on interception. Indirectly, temperature affects interception, since temperature affects the type of vegetation, but this itneraction is indirect and goes via primary producers and habitat supply.	No	There is no effect of interception on temperature. The amount of vegetation that influences interception may also influence temperature, but this is part of the component relating to primarty producers.
Water composition	Yes	Water composition may affect the amounts of water retained on the vegetation, e.g. some elements are more easily sorbed than others.	Yes	Extensive vegetation will inhibit fall out from reaching surface waters.

Bio38 Relocation

Variable	Variable influence on process		Process influence on variable	
	Influence present? Yes/No	**Description Comment**	**Influence present? Yes/No**	**Description Comment**
Geometry	Yes	The geometry of the landscape influences relocation, e.g. landslides are less likely in flat landscapes.	Yes	The extent of relocation may affect the landscape. Relocation is not considered to be an important process in the flat landscape of Forsmark. Relocation of sediment in marine basins are important but are caused by resuspension and resedimentation and thus covered by those processses.
Material composition	Yes	Characteristics of the regolith affect the potential for relocation.	Yes	Relocation that makes difference between particle size will affect the material composition.
Radionuclide inventory	No	There is no effect of radionuclide inventory on relocation.	Yes	Relocation may release contaminants and radionuclides to water and air and redistribute radionuclides from one point to another.
Stage of succession	Yes	Stage of succession affects the exposure to relocation, where wind erosion, solifluction and landsliding occurs in terrestrial habitats, whereas ice erosion mainly occurs in shallow aquatic ecosystems. These are, however, considered to be of low significance in the flat landscape of Forsmark.	Yes	Relocation of solid matter may affect stage of succession. The effect is considered to be of low significance compared to other processes such as deposition (see Bio34 above).
Temperature	Yes	Temperature may affect relocation at large temperature changes, e.g. solifluction is common in periglacial environments. Relocation in aquatic systems occur also during periglacial conditions, but other effects than temperature are assumed to have larger effect on relocation and this influence is not assuemd to be sigificant.	No	There is no effect of relocation on temperature.
Water composition	No	There is no direct effect of water composition on relocation.	No	There is no effect of relocation on water composition.

Bio39 Resuspension

Variable	Variable influence on process		Process influence on variable	
	Influence present? Yes/No	Description Comment	Influence present? Yes/No	Description Comment
Geometry	Yes	The geometry of the model domain affects the resuspenison, e.g. volumes of the regolith affects the amounts and likelihood of resuspension.	Yes	Resuspension affects the amount of regolith remaining and thus the geometry of the regolith.
Material composition	Yes	The size distribution of the particles in the regolith influences the amount of material resuspended in the water or air and thereby the particulate content in the water or air.	Yes	Resuspension is selective and affects material composition by resuspending particles of different sizes, due to the affecting force, e.g. wind and degree of exposure. For the regolith, the upper layer may be removed leaving lower layers with different composition from the resuspended matter.
Radionuclide inventory	No	There is no effect of radionuclide inventory on resuspension.	Yes	Resuspension may lead to a redistribution of radionuclides from regolith to water and air.
Stage of succession	Yes	Stage of succession affects resuspension, as resuspension is different in aquatic and terrestrial ecosystems.	Yes	Resuspension may lead to a redistribution of radionuclides from regolith to water and air.
Temperature	No	There is no effect of temperature on resuspension. resuspended.	No	There is no effect of resuspension on temperature.
Water composition	No	There is no direct effect of water composition on resuspension.	Yes	Resuspension affects water composition, especially the amounts of particles in water.

Bio40 Saturation

Variable	Variable influence on process		Process influence on variable	
	Influence present? Yes/No Description	**Handling of influence How/If not – Why**	**Influence present? Yes/No Description**	**Handling of influence How/If not – Why**
Geometry	Yes	Pore water content affects degree of saturation in different regolith layers in the drained and undrained mire, which will affect processes such as degassing and convection.	Yes	Saturation affect the depth of the zone in which water are transported.
Material composition	Yes	The porosity affects the degree of saturation in different regolith layers, which will affect processes such as degassing and convection.	No	There is no direct effect of saturation on material composition.
Radionuclide Inventory	No	There is no direct effect of radionuclide inventory on saturation.	No	There is no direct effect of saturation on radionuclide inventory. Indirectly, saturation may affect the distribution of radionuclides in different components of the biosphere if parts of the regolith is unsaturated, but this is handled via the process convection.
Stage of succession	Yes	Type pf ecosystem affects saturation, e.g. aquatic ecosystems always have saturated regolith, whereas terrestrial ecosystems may have unsaturated layers of regolith.	Yes	Continuing peat growth eventually develop the mire into bog-like conditions with restricted hydrological exchange and a more constant unsaturated peat layer.
Temperature	Yes	Temperature affect the depth of the saturated zone.	No	There is no direct effect of saturation on temperature.
Water composition	No	There is no direct effect of water composition on saturation.	No	There is no direct effect of saturation on water composition. Indirectly the depth of the regolith layer may affect the water composition due to different sorption properties at different depths but this goes via the process sorption/desorption.

Bio41 Radioactive decay

Variable	Variable influence on process		Process influence on variable	
	Influence present? Yes/No	Description Comment	Influence present? Yes/No	Description Comment
Geometry	No	There is no direct effect of geometry on radioactive decay.	No	There is no direct effect of radioactive decay on the geometry of the biosphere components.
Material composition	No	There is no direct effect of material composition on radioactive decay.	Yes	Decay of a large amount of unstable radionuclides may have an impact on the composition of regolith.
Radionuclide inventory	Yes	The radionuclide inventory affects radioactive decay, i.e. the radionuclides present determine the decay.	Yes	Radioactive decay affects the radionuclide inventory in all biosphere components.
Stage of succession	No	There is no direct effect of stage of succession on radioactive decay.	No	There is no direct effect of radioactive decay on stage of succession.
Temperature	No	There is no direct effect of temperature on radioactive decay.	Yes	Decaying radionuclides generate heat that may affect the temperature in the different components of the biosphere system.
Water composition	No	There is no direct effect of water composition on radioactive decay.	Yes	Decay of a large amount of unstable radionuclides may have an impact on the composition of water.

Bio42 Exposure

Variable	Variable influence on process		Process influence on variable	
	Influence present? Yes/No	**Description Comment**	**Influence present? Yes/No**	**Description Comment**
Geometry	Yes	The geometry affects the distribution of biosphere components and thereby the potential for exposure	No	There is no direct effect of exposure on geometry.
Material composition	Yes	Material may shield organism due to composition. to an extent that depends on its composition.	No	There is no direct effect of exposure on material composition.
Radionuclide inventory	Yes	Radionuclide inventory determines the magnitude of the exsposure.	No	There is no effect of exposure on radionuclide inventory.
Stage of succession	Yes	Different ecosystems may be inhabited by different types and amounts of organisms. For humans, the type of ecosystem is important and determines how the ecosystem is utlised and thereby routes of exposure.	No	There is no direct effect of exposure on stage of succession.
Temperature	No	There is no direct effect of temperature on exposure.	No	There is no direct effect of exposure on temperature.
Water composition	Yes	Water composition may shield organism due to composition. Water composition may affect the shielding of organisms. However, in natural ecosystems, water composition is not assumed to have significant effect on exposure, due to low concentrations of particles and solutes.	No	There is no effect of exposure on water composition.

Bio43 Heat storage

Variable	Variable influence on process		Process influence on variable	
	Influence present? Yes/No	Description Comment	Influence present? Yes/No	Description Comment
Geometry	Yes	The thicknesses and volumes of the environmental media determine the heat storage capacity.	No	There is no direct effect of heat storage on geometry.
Material composition	Yes	The composition and the grain size distribution of the materials in the regolith affect heat transport and thereby the temperature in the different components of the biosphere system.	No	There is no direct effect of heat storage on material composition.
Radionuclide inventory	No	There is no direct effect of radionuclide inventory on heat storage.	No	There is no direct effect of heat storage on radionuclide inventory.
Stage of succession	Yes	Stage of succession affects heat storage, since there is difference in heat storage between e.g. regolith and water. Also depths of aquatic basins are altered with succession influencing the geometry and thereby water turnover.	No	There is no direct effect of heat storage on stage of succession.
Temperature	Yes	Temperature affects the amount of heat that can be stored.	Yes	Heat storage affects the temperature of the different biosphere components
Water composition	Yes	The thermal properties of surface waters affect the heat storage capacity. The termal properties of water are assumed to be little altered by composition and the effect of heat storage capacty is assumed to be small.	No	There is no direct effect of heat storage on water composition. Heat storage may affect mixing and stratification, but this influence is handeled via the process convection.

Bio45 Light-related processes

Variable	Variable influence on process		Process influence on variable	
	Influence present? Yes/No	**Description Comment**	**Influence present? Yes/No**	**Description Comment**
Geometry	Yes	Geometry affects light-related processes, e.g. topography and bathymetry affect light attenuation, shading, light scattering etc.	Yes	Light-related processes affect the distribution and amounts (geometry) of primary producers.
Material composition	Yes	Material composition may affect the absorption of light and thereby influence light conditions in the biosphere components.	No	There is no direct effect of light-related processes on material composition.
Radionuclide inventory	No	There is no direct effect of radionuclide inventory on light-related processes.	No	There is no direct effect of light-related processes on the radionuclide inventory.
Stage of succession	Yes	Stage of succession affects light-related processes by determining the type of ecosystem and the depths of aquatic systems.	No	There is no direct effect of light-related processes on stage of succession.
Temperature	No	There is no direct effect of temperature on light-related processes.	Yes	Light-related processes affect the temperature of the system mainly by solar insolation.
Water composition	Yes	Light attenuation affecting primary producers is will indiectley affecxt water composition.	Yes	Light related processes may have an effect on water composition (e.g. UV radiation may affect the structure of organic carbon compounds), but the effect is assumed to be small compared with other factors influencing the water composition.

Bio47 Radionuclide release

Variable	Variable influence on process		Process influence on variable	
	Influence present? Yes/No	Description Comment	Influence present? Yes/No	Description Comment
Geometry	No	The geometry affects the transport of the released radionuclides after a release but there is no direct effect of geometry of the biosphere components on radionuclide release.	No	There is no direct effect of radionuclide release on geometry.
Material composition	No	The material composition of biosphere components affect the transport of radio-nuclides after a release but there is no direct effect of material composition of the biosphere on the radionuclide release.	No	The amounts of radionuclides in a safety assessment are too small to have a significant effect on material composition in the biosphere.
Radionuclide inventory	No	There is no direct effect of radionuclide inventory on radionuclide release.	Yes	Radinuclide release affects the radionuclide inventory in all parts of the biosphere system.
Stage of succession	No	The stage of succession affects the transport of radionuclides after a release, but there is no direct effect of stage of suc-cession on the radionuclide release.	No	There is no direct effect of radionuclide release on stage of succession.
Temperature	Yes	Temperature may affect radionuclide release, ground frost may affect the location of the release	No	The concentrations of radionuclides in a safety assessment are too small to have a significant effect on temperature in the biosphere.
Water composition	No	The water composition affects the transport of radi-onuclides after a release, but there is no direct effect of water composition of surface water or water in regolith on the radionuclide release.	No	The concentrations of radionuclides in a safety assessment are too small to have a significant effect on water composition in the biosphere.

Bio48 Change in rock surface location

Variable	Variable influence on process		Process influence on variable	
	Influence present? Yes/No	Description Comment	Influence present? Yes/No	Description Comment
Geometry	Yes	Geometry is affected by changes in rock surface location, but does not normally affect the process. Exceptions are during glacial epriods where the the height of the ice supress the bedrock.	Yes	Isostatic rebound changes the rock surface location and can change the height of the regolith and thereby change the geometry of the landscape.
Material composition	No	There is no direct effect of material composition on change in rock surface location.	No	There is no direct effect of change in rock surface location on material composition.
Radionuclide inventory	No	There is no direct effect of radionuclide inventory on change in rock surface location.	No	Change in rock surface location may indirectly affect the fluxes of radionuclides (process convection), but there is no direct effect of change in rock surface location on radionuclide inventory.
Stage of succession	No	There is no direct effect of stage of succession on change in rock surface location.	Yes	Change in rock surface location is one of the driving factors leading to landscape development and succession of the ecosystems from marine to limnic to terrestrial areas.
Temperature	Yes	Temperature affects change in rock surface location indirectly during glacial periods when ice forms and and supress the rock surface.	No	There is no direct effect of change in rock surface location on temperature.
Water composition	No	There is no direct effect of water composition on change in rock surface location.	No	There is no direct effect of change in rock surface location on water composition.

Bio49 Sea level change

Variable	Variable influence on process		Process influence on variable	
	Influence present? Yes/No	**Description Comment**	**Influence present? Yes/No**	**Description Comment**
Geometry	Yes	The geometry of the sea water affects the sea level.	Yes	Sea level change affects the geometry of aquatic basins and terrestrial areas.
Material composition	No	There is no direct effect of material composition on sea level change	No	There is no direct effect of sea level change on material composition.
Radionuclide inventory	No	There is no direct effect of radionuclide inventory on sea level change.	No	There is no direct effect of sea level change on radionuclide inventory. Sea level change may lead to terrestrialisation and a shift of radionuclides from an aquatic regolith to an terrestrial one, but this is included in other processes (such as relocation).
Stage of succession	No	There is no direct effect of stage of succession on sea level change.	Yes	Sea level change contributes to succession of ecosystems.
Temperature	Yes	Temperature affects sea level change and at present worldwide sea levels are rising due to expansion of the water volume with increasing temperatures.	No	There is no direct effect of sea level change on temperature.
Water composition	No	There is no direct effect of water composition on sea level change.	No	There is no direct effect of sea level change on water composition.

Bio50 Thresholding

Variable	Variable influence on process		Process influence on variable	
	Influence present? Yes/No	**Description Comment**	**Influence present? Yes/No**	**Description Comment**
Geometry	Yes	The geometry of the landscape determines where there are thresholds and sets the boundaries between lakes and sea.	Yes	Thresholding determines the geometries of water bodies (volume, area, depth etc).
Material composition	Yes	Material composition affects the location of thresholds (i.e. affect whether a material is prone to erosion or remain as a threshold).	No	There is no direct effect of thresholding on material composition.
Radionuclide inventory	No	There is no direct effect of radionuclide inventory on thresholding.	No	There is no direct effect of thresholding on radionuclide inventory.
Stage of succession	No	There is no direct effect of stage of succession on thresholding.	Yes	Thresholds set the boundaries between lakes and sea and thereby influence the stage of succession.
Temperature	No	There is no direct effect of temperature on thresholding.	No	Thresholding may affect currents and water fluxes and thereby indirectly affect temperature, but there is no direct effect of thresholding on temperature.
Water composition	No	There is no direct effect of water composition on thresholding.	No	There is no direct effect of thresholding on water composition.

Appendix D

List of process names

In SKB's previous work, different names have been used for the same process. Here, previous names as well as certain names commonly used in the literature are listed together with the process names currently used in the biosphere IM and a reference to the group of processes in which they are described. Since some of the processes are composed of a number of sub-processes (for example, reactions may include thousands of specific chemical reactions), not all sub-processes are included in this table; instead, the table is limited to certain commonly used names for the processes considered in the safety assessment for the biosphere.

Process name (previously used by SKB or commonly used in the literature)	Process name in the present report	Group of processes
Absorption	Sorption/desorption, Light-related processes	Chemical, mechanical and physical processes, Thermal and radiological processes
Adiabatic compression	Change of pressure	Chemical, mechanical and physical processes
Adiabatic temperature change	Change of pressure	Chemical, mechanical and physical processes
Adsorption	Sorption/desorption	Chemical, mechanical and physical processes
Advection	Convection	Transport processes
Anthropogenic effects	Anthropogenic release	Biological processes
Aquaculture	Species introduction/extermination	Biological processes
Artificial infiltration	Water use	Biological processes
Attenuation	Light-related processes	Thermal and radiological processes
Breakdown	Decomposition	Biological processes
Capillary rise	Convection	Transport processes
Change in water content	Saturation	Transport processes
Chemical equilibrium	Reactions	Chemical, mechanical and physical processes
Chemical reactions	Reactions	Chemical, mechanical and physical processes
Chemosynthesis	Primary production	Biological processes
Colonisation	Species introduction/extermination	Biological processes
Condensation	Phase transitions	Chemical, mechanical and physical processes
Contaminant transport	Radionuclide release	Thermal and radiological processes
Continental rebound	Change in rock surface location	Landscape development processes
Crystal water release	Reactions	Chemical, mechanical and physical processes
Cultivation	Species introduction/extermination	Processes related to human behavior
Damming	Water use	Processes related to human behavior
Decay	Radioactive decay	Radiological and thermal processes
Degassing	Phase transitions	Chemical, mechanical and physical processes
Degradation	Reaction	Chemical, mechanical and physical processes
Dehydration	Excluded	Irrelevant process in a radionuclide perspective
Density effect	Physical properties change	Chemical, mechanical and physical processes
Diffusion	Convection	Transport processes
Discharge	Convection	Transport processes
Dispersal	Species introduction/extermination	Processes related to human behavior
Dissolution	Phase transitions, Reactions	Chemical, mechanical and physical processes
Dissolution/ precipitation	Phase transitions, Reactions	Chemical, mechanical and physical processes
Disturbance	Relocation	Transport processes
Drinking	Uptake	Biological processes
Dry deposition	Deposition	Transport processes
Earthquakes	Change in rock surface location	Landscape development processes
Eating	Consumption	Biological processes
Emigration	Export	Transport processes
Emissions	Anthropogenic release	Biological processes
Erosion	Relocation	Transport processes
Eustasy	Sea level change	Landscape development processes
Evaporation	Phase transitions	Chemical, mechanical and physical processes

Process name (previously used by SKB or commonly used in the literature)	Process name in the present report	Group of processes
Evapotranspiration	Phase transitions	Chemical, mechanical and physical processes
Exotherm/ Endotherm reactions	Reactions	Chemical, mechanical and physical processes
Export of energy	Export	Transport processes
Export of heat	Export	Transport processes
Export of primary producers	Export	Transport processes
Extermination	Species introduction/extermination	Processes related to human behavior
External exposure	Exposure	Thermal and radiological processes
External load of contaminants	Import	Transport processes
Extinction	Species introduction/extermination	Processes related to human behaviour
Farming	Species introduction/extermination	Processes related to human behaviour
Feeding	Consumption	Biological processes
Fermentation	Decomposition	Biological processes
Fertilizing	Anthropogenic release	Processes related to human behaviour
Filtering	Water use	Biological processes
Fire	Reactions	Chemical, mechanical and physical processes
Formation of stabile isotopes	Decay	Thermal and radiological processes
Freezing	Phase transitions	Chemical, mechanical and physical processes
Gas transport	Convection	Transport processes, Processes at the boundary
Gas uptake	Uptake	Biological processes
Geometric extension	Thresholding	Landscape development processes
Hail	Deposition	Transport processes
Heat capacity	Heat storage	Thermal and radiological processes
Heat from decay	Decay	Thermal and radiological processes
Heat transport	Convection	Transport processes
Human activities	Anthropogenic release, Consumption, Material use, Water use	Processes related to human behavior
Human intrusion	Intrusion	Biological processes
Ice load	Loading	Chemical, mechanical and physical processes
Immigration	Import	Transport processes
Import of energy	Import	Transport processes
Import of heat	Import	Transport processes
Infilling	Stage of succession	A feature
Ingestion	Consumption	Biological processes
Insolation	Light-related processes	Thermal and radiological processes
Internal exposure	Exposure	Thermal and radiological processes
Ion exchange	Sorption/desorption	Chemical, mechanical and physical processes
Ionising radiation	Irradiation	Thermal and radiological processes
Irrigation	Water use	Processes related to human behaviour
Isostatic adjustment	Change in rock surface location	Landscape development preocesses
Kinetics	Reactions	Chemical, mechanical and physical processes
Lake infilling	Stage of succession	A feature
Land-rise	Change in rock surface location	Landscape development processes
Landslide	Relocation	Transport processes
Leaching	Phase transitions	Chemical, mechanical and physical processes
Light absorption	Light-related processes	Thermal and radiological processes
Light attenuation	Light-related processes	Thermal and radiological processes
Light reflection	Light-related processes	Thermal and radiological processes
Light scattering	Light-related processes	Thermal and radiological processes
Living and building	Anthropogenic release, Material use, Water use, Consumption	Biological processes, Processes related to human behaviour
Locomotion	Movement	Biological processes
Mass flux	Convection	Transport processes
Mechanical load	Loading	Chemical, mechanical and physical processes
Migration	Import, Export	Transport processes
Mixing	Convection	Transport processes
Neotectonic movements	Change in rock surface location	Landscape development processes
Net primary production	Primary production, Food supply, Growth	Biological processes

Process name (previously used by SKB or commonly used in the literature)	Process name in the present report	Group of processes
Non-biological decomposition	Reactions	Chemical, mechanical and physical processes
Oxidation	Reactions	Chemical, mechanical and physical processes
Particle production	Particle release/trapping	Biological processes
Partitioning	Sorption/desorption	Chemical, mechanical and physical processes
Phase changes	Phase transitions	Chemical, mechanical and physical processes
Photochemical reactions	Reactions	Chemical, mechanical and physical processes
Photosynthesis	Primary production	Biological processes
Pingo formation	Phase transitions	Chemical, mechanical and physical processes
Plant intrusion	Intrusion	Biological processes
Pollution	Anthropogenic release	Biological processes
Post-glacial rebound	Change in rock surface location	Landscape development processes
Precipitation	Deposition, Phase transitions	Transport processes, Chemical, mechanical and physical processes
Primary compression	Consolidation	Chemical, mechanical and physical processes
Rainfall	Deposition	Transport processes
Recharge	Convection	Transport processes
Reduction	Reactions	Chemical, mechanical and physical processes
Reflection	Light-related processes	Thermal and radiological processes
Regolith volume reduction	Consolidation	Chemical, mechanical and physical processes
Release	Excretion	Biological processes
Relocation in water	Relocation	Transport processes
Relocation on land	Relocation	Transport processes
Resource	Material supply	Biological processes
Retardation	Acceleration	Transport processes
Root growth	Bioturbation	Biological processes
Root penetration (biological)	Intrusion, Bioturbation	Biological processes
Root penetration (Rock)	Intrusion	Biological processes
Root uptake	Uptake	Biological processes
Runoff	Convection	Transport processes
Scattering	Light-related processes	Thermal and radiological processes
Sea currents	Convection	Transport processes
Sea spray	Resuspension	Transport processes
Secondary production	Food supply, Growth	Biological processes
Sedimentation	Deposition	Transport processes
Settlement	Habitat supply, Stimulation/inhibition	Biological processes
Sewage	Anthropogenic release	Processes related to human behavior
Shoreline displacement	Change in rock surface location	Landscape development processes
Showering	Water use	Processes related to human behavior
Snowdrift	Resuspension	Transport processes
Snowfall	Deposition	Transport processes
Sublimation	Phase transitions	Chemical, mechanical and physical processes
Surface deposition	Deposition	Transport processes
Transpiration	Phase transitions	Chemical, mechanical and physical processes
Uptake/Excretion	Uptake, Excretion	Biological processes
Volume expansion/ contraction	Physical property change	Chemical, mechanical and physical processes
Washing	Water use	Processes related to human behaviour
Water extraction	Water use	Processes related to human behaviour
Water flow	Convection	Transport processes
Water flux	Convection	Transport processes
Water pumping	Water use	Processes related to human behaviour
Water transport	Convection	Transport processes
Water uptake	Uptake	Biological processes
Wave formation	Acceleration	Transport processes
Wet deposition	Deposition	Transport processes
Wind field changes	Acceleration	Transport processes
Wind retardation	Acceleration	Transport processes
Wind velocities	Acceleration	Transport processes