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Components, processes and interactions in the biosphere

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1 Introduction

This report describes the processes and interactions between components in the biosphere that may be important in a safety assessment for radioactive waste disposal. The processes are general, i.e. they can be used in all safety analyses 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, SKB 2001, 2006, 2010a/. This report describes a biosphere interaction matrix that has been used in support of SR-Site and that can be used in future safety assessments. 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 processes (see Table 1-1).

1.1 Background

In a safety assessment for the biosphere, it is necessary to understand how the ecosystems function to be able to predict pathways and sinks of radionuclides in the ecosystem and, primarily, doses to humans and other biota. One step in a safety assessment of the biosphere is to identify the boundary of the 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. It is sometimes difficult to make a clear distinction between biosphere and geosphere and some sets f 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 overlaying atmosphere (Figure 1-1).

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 division into distinct ecosystems makes it easier to identify interactions in the biosphere system. This report concerns all types of ecosystems, although some processes may be more or less important in different ecosystems.

Another step in a safety assessment for a repository for radioactive waste is to identify all factors that are important for the ecosystem today and in the future from a radioecological point of view. Each ecosystem 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 in a safety assessment. However, a systematic approach to the identification and characterisation of relevant processes and interactions is important in order to identify and include all important processes affecting the transport

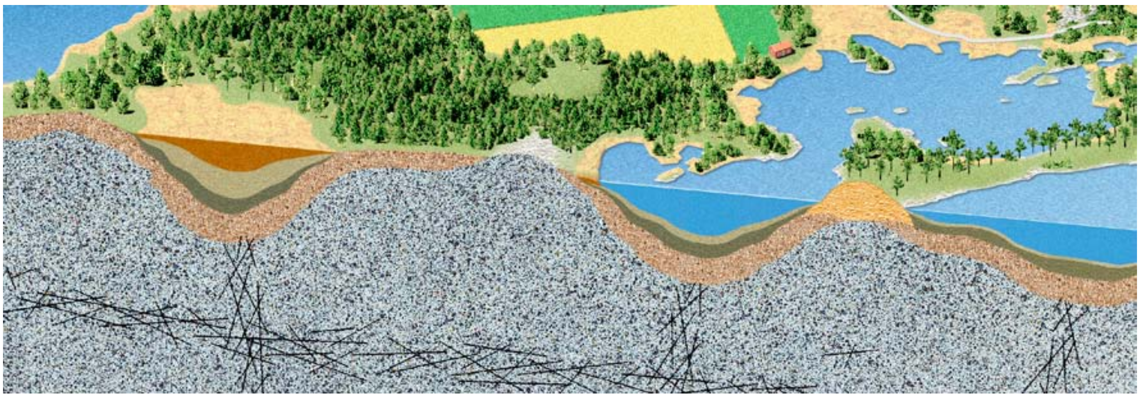

Figure 1-1. The biosphere includes regolith, hydrological and subsurface hydrogeological systems, biota (including humans), and the overlaying atmosphere.

and accumulation of radionuclides in the biosphere. One way to systematically identify important processes is to construct an interaction matrix (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 radiation dose 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 setting up radionuclide transport models, the IM may also be used in the planning of site investigations and ecosystem modelling. Site investigations, ecosystem models, and radionuclide transport models, along with other scientific research, are the most important tools in long-term efforts to improve our understanding of ecosystem function and radionuclide behaviour. These models may also generate information that can be used to update and improve the IM (Figure 1-2).

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 an early version of an IM for the biosphere was described in 2001 /Kautsky 2001, SKB 2001/. In parallel with SKB's early work on interaction matrices, others also produced interaction matrices for ecosystems, e.g. /Avila and Moberg 1999, Velasco et al. 2006, Haapanen et al. 2009/. However, with the exception of /Haapanen et al. 2009/, these interaction matrices do not always reflect an understanding of the processes involved, but are rather to be viewed as transfer matrices illustrating transfer parameters between different components of the system. The International Atomic Energy Agency (IAEA) has produced a database of Features, Events, and Processes (FEPs) that are used in safety assessments of repositories for radioactive waste by a number of countries. All IAEA FEPs associated with the biosphere are included in the process definitions given here (unless they are clearly irrelevant for Swedish situations). Definitions of IAEA FEPs and how they correlate to the process names used by SKB can be found in SKB's database of FEPS /SKB 2010a/.

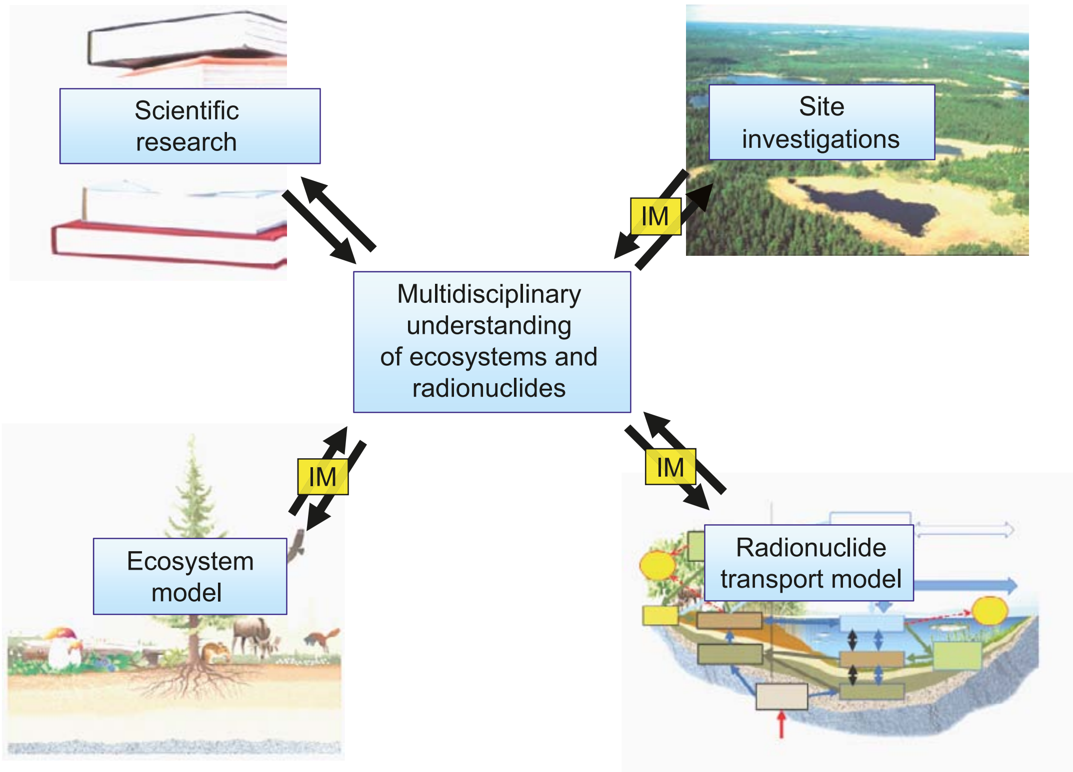

Figure 1-2. *A general understanding of the system in question is vital when setting up radionuclide transport models in a safety assessment. Scientific research, site investigations and ecosystem models may be used to improve this understanding, and interactions matrices may be used as a tool to ensure 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 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 (the updated IM is presented in this report).

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. Since then, many processes have been renamed and grouped differently to make the matrix more comprehensive. Reviewers have contributed substantially to the development of the IM, and we would especially like to thank Mike Thorne. Note that the professional affiliations of persons involved in the development of the initial interaction matrix in 2001 may have changed.

Person	Expertise	Participated in the development of the initial biosphere matrix (IBIM) or the developed biosphere interaction matrix described in this report (DBIM)
Ulrik Kautsky SKB	Project manager for the work with the interaction matrix and process definitions for the biosphere, System ecology, Radio-ecology, Safety assessments	IBIM and DBIM
Eva Andersson Studsvik Nuclear AB	Editor of this report, Limnology	DBIM
Karin Aquilonius Studsvik Nuclear AB	Marine biology	DBIM
Ulla Bergström Studsvik Ecosafe AB	Radiochemistry	IBIM
Lars Brydsten Umeå University	Physical geography	IBIM
Anders Engqvist A&I Engqvist consult AB	Oceanography	IBIM
Martin Isaeus Stockholm University	Botany	IBIM
Linda Kumblad Stockholm University	System Ecology	IBIM
Tobias Lindborg SKB	Terrestrial ecology, Safety assessment	IBIM and DBIM
Angelica Lorentzon SKB	System ecology	DBIM
Anders Löfgren EcoAnalytica	Terrestrial ecology	DBIM
Marcus Meili Uppsala University	Limnology	IBIM
Kristina Skagius Kemakta Konsult AB	Migration processes, Safety assessment	IBIM
Björn Söderbäck SKB	Limnology	DBIM
Marie Wiborgh Kemakta Konsult AB	Chemistry, safety assessment	IBIM

2 This report

This chapter presents the objectives of this report and serves as a guide for the reader as it describes how the different chapters are related. The report was produced within the SR-Site project and this chapter puts the report in a broader context describes how this report relates to other work within SR-Site.

2.1 Objectives

In this report, a general biosphere IM is presented along with definitions of processes that are important for radionuclide transport in the biosphere. The aims of this report are as follows:

- Produce a description of processes in general terms but not ecosystem-specific ones. This description should include processes considered in current SKB safety assessments but, should be sufficiently wide ranging to be used for future safety assessments.
- To present a general IM for the biosphere that may be used as a basis for future safety assessments.

2.2 SR-Site safety assessment

The present report is produced within the SR-Site project but is also intended to be valid for future safety assessments of the biosphere. Radioactive waste from nuclear power plants in Sweden is managed by the Swedish Nuclear Fuel and Waste Management Co, SKB. Spent nuclear fuel from the power plants is planned to be placed in a geological repository according to the KBS-3 method. In this method, copper canisters with a cast iron insert containing spent fuel are surrounded by bentonite clay and deposited at approximately 500 m depth in saturated, granitic rock. Around 12,000 tonnes of spent nuclear fuel is forecasted to arise from the Swedish nuclear power programme, corresponding to roughly 6,000 canisters in a KBS-3 repository.

Between 2002 and 2007, SKB performed site investigations at two different sites along the eastern coast of southern Sweden; Forsmark in the municipality of Östhammar and Laxemar-Simpevarp in the municipality of Oskarshamn, with the intention of identifying a safe location for the repository. Data from the site investigations were used to produce a comprehensive, multi-disciplinary site description for each of the sites. The resulting site descriptions were reported in /SKB 2008/ (Forsmark) and /SKB 2009/ (Laxemar-Simpevarp). Based on available knowledge from the site descriptions and from preliminary safety assessments of the planned repository, SKB in June 2009 to selected Forsmark as the site for the repository. The location of Forsmark is shown in Figure 2-1. An application for the construction of a geological repository for spent nuclear fuel at Forsmark is planned to be filed in 2011.

According to the regulations from the Swedish Radiation Safety Authority, SSM, a safety assessment of the planned repository, evaluating features, events and processes that potentially may lead to the release of radionuclides, has to be performed before the construction of the repository is started (SSMFS 2008:21). The evaluation of the long-term safety of the repository is reported in the SR-Site main report /SKB 2011/ (SR-Site is the project of which the report is a product) and, accordingly, it is an important supporting document to the application. The present report is produced within the SR-Site project and is a support in defining important features events and processes in the biosphere.

The safety assessment SR-Site, which is described in the SR-Site main report /SKB 2011/, is focused on three major fields of investigation: the performance of the repository, the geosphere and the biosphere. The biosphere part of SR-Site, SR-Site Biosphere, provides estimates for human exposure given a unit release (*Landscape Dose Conversion Factors*). Multiplying these factors with modelled release rates from the geosphere results in estimates of the annual doses used to assess compliance with the regulatory risk criterion. The effects on the environment of a potential release from the repository are also assessed in SR-Site Biosphere. In order to assess effects on the environment, features and processes of importance for radionuclide transport, accumulation n and exposure are identified in this report.

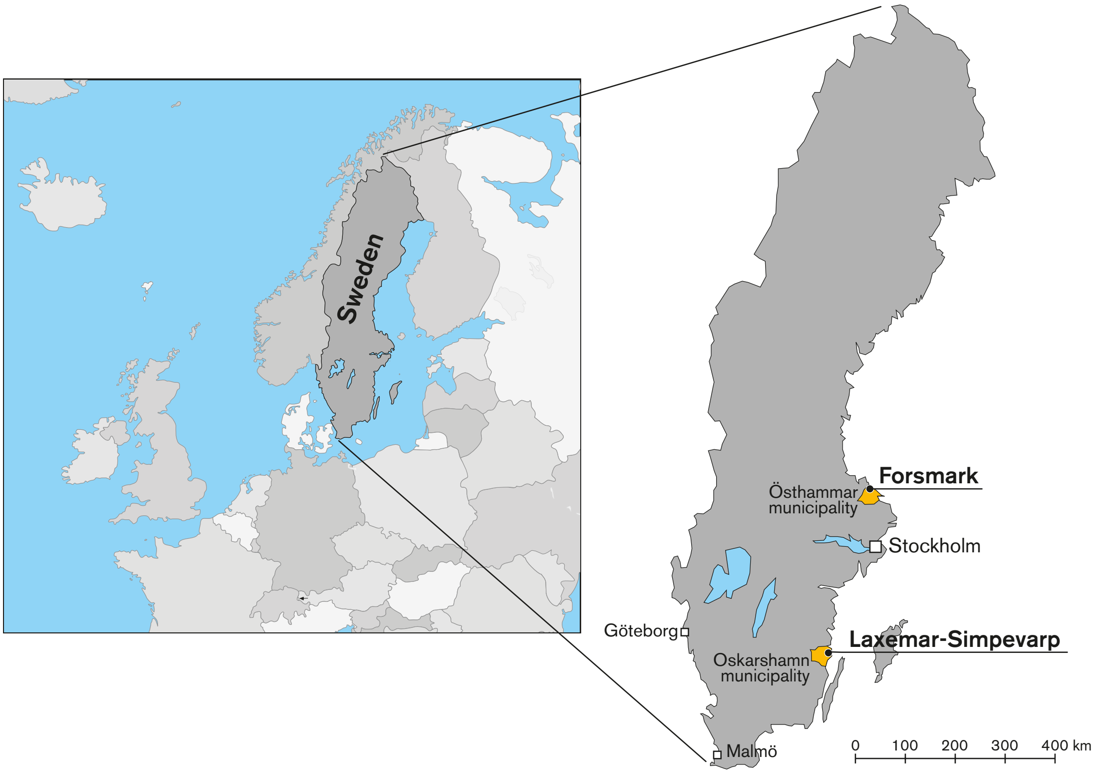

Figure 2-1. Location of the Forsmark site.

The main document for the biosphere analysis within the SR-Site Safety assessment is the Biosphere synthesis report /SKB 2010b/. However, a number of background reports are produced were all details and data which are necessary for a detailed review and for a reconstruction of the work done can be found. Figure 2-2 show information flow between the reports and how the reports are linked together.

The work done within the biosphere assessment in SR-Site has been conducted by a number of people (Table 2-1). This group has been involved from the beginning of the site investigation, via the site characterization and modelling tasks, and in this final synthesis for the safety assessment SR-Site. As a result, although not all are directly involved in the development of the biosphere interaction matrix, they are indirectly involved since they have all contributed to the understanding of the biosphere and radionuclide behaviour in the biosphere.

2.3 Overview of contents

This report consists of a number of definitions and descriptions of biosphere components and processes. The definitions are generally accepted and, where appropriate, references are given to the source of the definition. However, since processes are complex, and since some processes are lumped together here, process names and definitions may differ somewhat from those used in the literature. This document describes how SKB uses the process names and defines the different components of the biosphere. These definitions can in some cases be broader or narrower than those used by other authors.

Chapter 3 describes the concept of interaction matrices (IM) and the development of the biosphere IM.

Chapter 4 describes the overall biosphere IM.

Chapter 5 describes the diagonal elements of the biosphere IM.

Chapter 6 presents definitions of processes in the biosphere IM. In order to illustrate the different kinds of processes that occur in the biosphere, the processes are divided into 6 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.

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

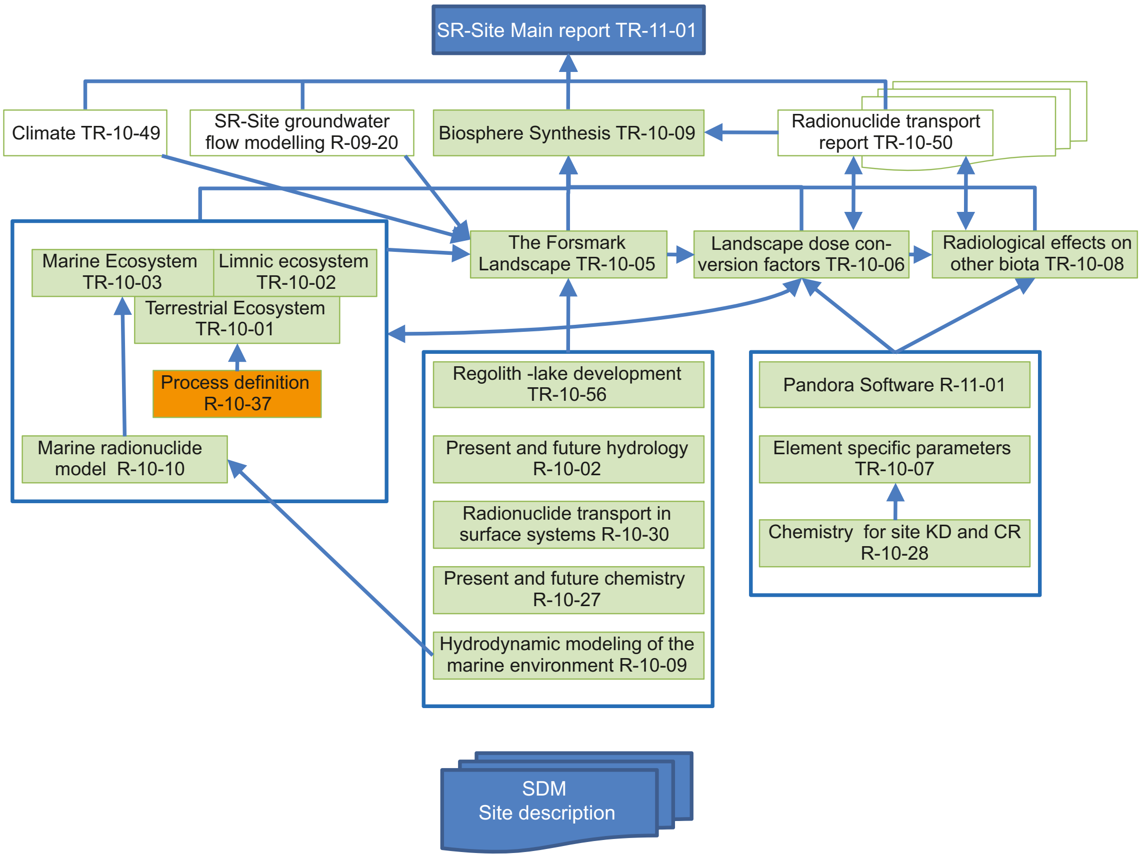

Figure 2-2. *The hierarchy of reports produced in the SR-Site Biosphere project. This report (market red) and its dependencies on information from subordinate biosphere reports and other reports within SR-Site. Arrows indicates major interactions during project work flow of analysis and results, but interaction has been substantial between most parts of the project throughout the process. The sources of data should be searched for in subordinate reports if not explicitly pointed to in text. SDM is the site descriptive model /Lindborg (ed.) 2008/.*

Table 2-1. The project members involved in the biosphere analysis within the SR-Site Safety assessment in alphabetic order, their affiliation and role are listed below.

Eva Andersson**, Studsvik Nuclear AB	process descriptions and limnic ecosystems
Karin Aquilonius, Studsvik Nuclear AB	marine ecosystems
Rodolfo Avila, Facilia AB	radionuclide modelling and dose assessment
Sten Berglund, SKB	hydrology and near-surface radionuclide transport
Emma Bosson, SKB	surface hydrology and near-surface hydrology
Lars Brydsten, Umeå University	regolith dynamics and lake development and GIS analysis
Anders Clarhäll, SKB	editorial work
Per-Anders Ekström, Facilia AB	numerical modelling
Anders Engqvist, KTH	oceanography
Sara Grolander, Facilia AB	site specific chemical data
Anna Hedenström, SGU	regolith
Ulrik Kautsky*, SKB	overall biosphere assessments project leader, scientific and method development
Tobias Lindborg*, SKB	site modelling and landscape development
Angelica Lorentzon af Ekenstam, SKB	process description and project administration
Anders Löfgren, EcoAnalytica	terrestrial ecosystems and synthesis
Sara Nordén, SKB	radionuclide and element specific properties
Peter Saetre, SKB	data evaluation, synthesis and review of results, editor of this report
Mona Sassner, DHI	surface hydrology
Gustav Sohlenius, SGU	regolith and future land use
Mårten Strömgren, Umeå University	GIS analysis, landscape development
Björn Söderbäck, SKB	site descriptions and historical development
Jesper Torudd, Facilia AB	non-human biota assessment
Mats Tröjbom, MTK AB	biogeochemistry and mass balances
Per-Gustav Åstrand, Facilia AB	numerical modelling

*project leader SR-Site Biosphere

**assistant project leader SR-Site Biosphere

3 Concept of an interaction matrix and methodology

The transport and accumulation of radionuclides in the biosphere involves a large number of biotic and abiotic interactions. In a safety assessment, it is important to ensure that all important radionuclide transfer pathways are addressed. Using a systematic approach such as interaction matrices (IM) makes it likely that the major transfer pathways will be included, or else a clear reason given as to why they are omitted /Avila and Moberg 1999, Velasco et al. 2006, Harrison and Hudson 2006/. Figure 3-1 shows a conceptual model of an aquatic ecosystem. 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 complete IM. The development of an IM, therefore, generally involves experts from different disciplines in a series of documented meetings. SKB produced an initial IM for the biosphere in the SAFE project with the aid of experts from several disciplines (Table 1-1 and /SKB 2001/). That IM has since been further refined by experts at several meetings, and the resulting IM is presented in Chapter 3.

The general principles of an IM are illustrated in Figure 3-2. The system of interest (in the case of biosphere IM, an ecosystem) is divided into various components that are listed along the lead diagonal of the matrix. These components are referred to as diagonal elements in the following. Processes that relate the diagonal elements, interactions, are entered in the off-diagonal elements, as shown in Figure 3-2. Note that the matrix is read in a clockwise sense, 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. It is important to ensure that the effects of processes are direct and are not mediated by interactions via a third element listed on the lead diagonal.

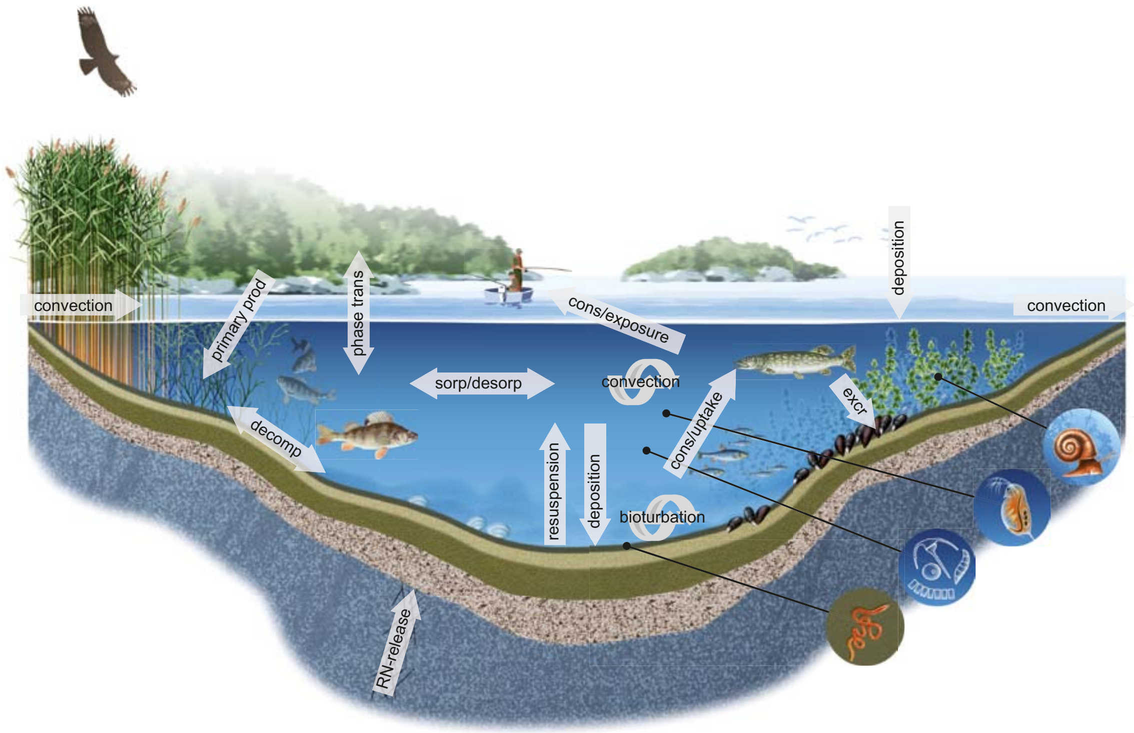

Figure 3-1. *Example of an ecosystem model: a conceptual model of an aquatic ecosystem. Arrows illustrate processes (e.g. consumption, excretion and convection) whereby different components of the aquatic ecosystem affect each other. Abbreviations reads as follows: cons.=consumption, decomp.=decomposition, excr.=excretion, phase trans.=phase transitions, RNrelease= radionuclide release, sorp./desorp.=sorption/desorption.*

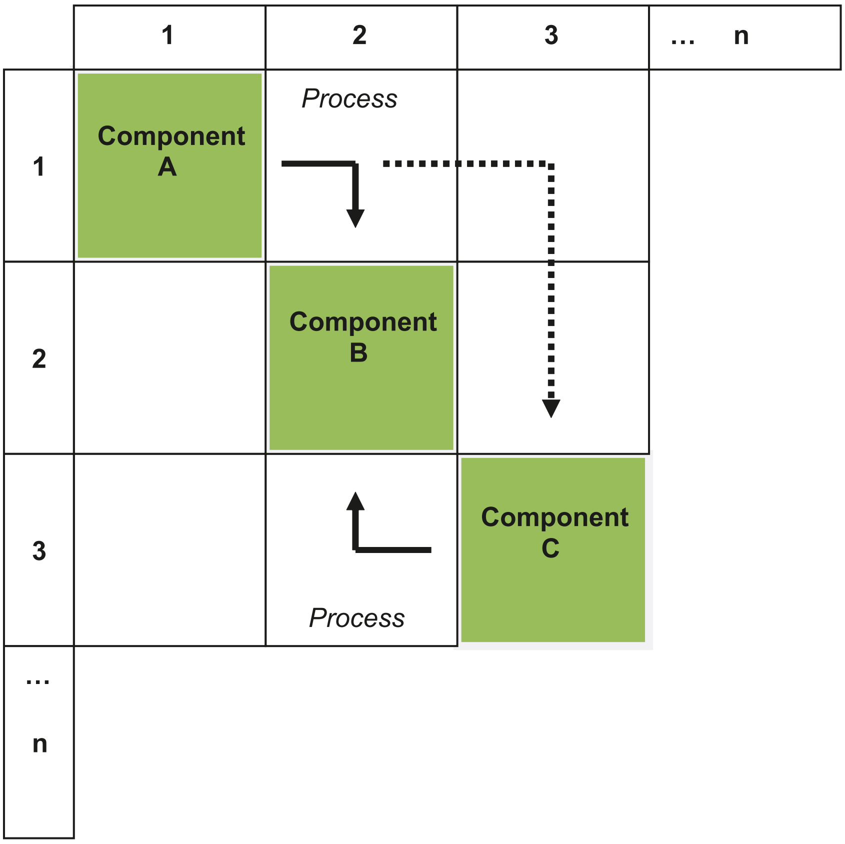

Figure 3-2. Conceptual illustration of an interaction matrix. The diagonal elements A, B and C are key components of the ecosystem and are placed on the diagonal. The off-diagonal elements (white boxes) represent one or more processes. The arrows illustrates e.g. how Component A (1,1) affects Component 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.

The diagonal elements of a system are defined by exploring how the state of the system can be described in terms of physical components, spatial and temporal extension of the system and initial and boundary conditions of the system. The diagonal elements may be either spatially or conceptually distinct. Thus, for example, two elements might be water in regolith and surface water (physically distinct) or herbivores and carnivores (conceptually distinct). An element may also be a property, such as temperature. The number of diagonal elements is a measure of matrix resolution. If the number of leading diagonal terms increases, then the number of possible interaction terms and the matrix resolution also increase. To keep the number of diagonal elements manageable there are processes acting within the 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, dividing biota into different species would result in an unmanageably large IM, whereas lumping all 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.

The dynamics of an ecosystem can be described in terms of processes between the major components (diagonal elements in the matrix), where the processes are interactions between the components. Specifying all the processes in an ecosystem is not feasible, and from the perspective of radionuclide transport and accumulation it is also unnecessary. Instead, processes similar to each other and/or with a similar mechanism or result have, in this report, been grouped into larger comprehensive processes. As an example from the biosphere IM, the process 'reaction' includes chemical reactions in water and within biota (metabolic reactions), which means that this one process includes hundreds (or even thousands) of possible sub-processes if all separate reactions were treated individually. Another example is the process ‘deposition’, which includes wet and dry deposition, sedimentation, and precipitation. This simplifies the pictorial illustration of the ecosystem, although, at a later stage, when the IM elements are used in a model, the underlying processes and parameters have to be explored in greater detail.

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 of this is gravitation, which causes deposition (which is described). The Earth’s gravitation is an inward-acting force by means of which the Earth tends to pull objects towards its centre /Skinner and Porter 2000/. 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 behaviour are included.

When modelling potential future characteristics, time-dependent properties, such as the predicted future landscape development are needed in the model. Therefore, processes such as glaciation and isostatic rebound may be included in an IM. The IM produced here is valid for a glacial cycle, i.e. including temperate, periglacial and glacial conditions, although the primary focus is on a temperate climate. Only climate conditions that may occur in Sweden are included, which means that processes connected with other climate regions such as rainforests or deserts are not considered in this report.

It is also possible to grade each process in the matrix according to its estimated importance in the specific ecosystem. In safety assessments for radioactive waste disposal, knowledge of radionuclide behaviour in ecosystems is included when evaluating processes, i.e. a process may be important from an ecological point of view but unimportant for radionuclide transport and accumulation. Moreover, a process may be important in an interaction between two given components, but not important in an interaction between two other components. It is, therefore, difficult to specify the importance of individual processes in general terms. Furthermore, a process may be important in one ecosystem and not in another. The importance of different interactions in limnic, marine and terrestrial ecosystems at Forsmark is described in /Andersson (ed) 2010, Aquilonius (ed) 2010, Löfgren (ed) 2010/.

4 Biosphere IM

A general IM for ecosystems in a temperate climate is presented in Figure 4-1. The IM includes 15 diagonal elements and 51 processes further described in the following sections.

The IM can be used as a tool to check that important processes in site investigations and models are included. However, as the matrix is general, all process interactions may not be of importance for all ecosystems. Some of the processes are of little importance in all ecosystems, but are still listed so that the IM will be comprehensive. Some interactions are ecosystem-specific, for example filter feeders are present only in aquatic ecosystems. Others interactions are specific to terrestrial ecosystems. For details of the importance of different processes in specific ecosystems, readers are referred to the chapters on IMs in the ecosystem reports in SR-site /Andersson (ed) 2010, Aquilonius (ed) 2010, Löfgren (ed) 2010/.

	1	2	3	4	5	6	7	8
1	**GEOSPHERE (B.C.)**	a) Change in rock surface location b) Weathering						a) Material supply
2	a) Consolidation b) Loading	**Regolith**	a) Element supply b) Habitat supply c) Light related processes d) Relocation	a) Element supply b) Food supply c) Habitat supply	a) Food supply b) Habitat supply	a) Habitat supply	a) Habitat supply	a) Food Supply b) Habitat supply c) Material supply
3	a) Intrusion	a) Bioturbation b) Death	**Primary producers**	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) Habitat supply b) Stimulation/inhibition	a) Food supply b) Material supply c) Stimulation/inhibition
4	a) Intrusion	a) Bioturbation b) Consumption c) Death d) Decomposition	a) Stimulation/inhibition	**Decomposers**	a) Food supply b) Stimulation/inhibition	a) Food supply b) Stimulation/inhibition	a) Food supply b) Stimulation/inhibition	a) Food supply b) Material supply c) Stimulation/inhibition
5	a) Intrusion	a) Bioturbation b) Death	a) Consumption b) Habitat supply c) Stimulation/inhibition	a) Consumption b) Habitat supply c) Stimulation/inhibition	**Filter feeders**	a) Consumption b) Stimulation/inhibition	a) Consumption b) Food supply c) Stimulation/inhibition	a) Food supply b) Material supply c) Stimulation/inhibition
6	a) Intrusion	a) Bioturbation b) Death	a) Consumption b) Stimulation/inhibition	a) Stimulation/inhibition	a) Food supply b) Stimulation/inhibition	**Herbivores**	a) Food supply b) Stimulation/inhibition	a) Food supply b) Material supply c) Stimulation/inhibition
7	a) Intrusion	a) Bioturbation b) Death	a) Stimulation/inhibition	a) Consumption b) Stimulation/inhibition	a) Consumption b) Food supply c) Stimulation/inhibition	a) Consumption b) Stimulation/inhibition	**Carnivores**	a) Consumption b) Food supply c) Material supply d) Stimulation/inhibition
8	a) Intrusion b) Material use	a) Death b) Material use c) Relocation	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) Material use c) Species introduction/ extermination e) Stimulation/inhibition	**Humans**
9	a) Change of pressure b) Convection c) Weathering	a) Relocation b) Saturation	a) Habitat supply b) Water supply	a) Habitat supply b) Water supply	a) Water supply	a) Water supply	a) Water supply	a) Water supply
10	a) Change of pressure b) Convection c) Loading d) Weathering	a) Relocation b) Resuspension	a) Habitat supply b) Relocation c) Water supply	a) Habitat supply b) Relocation c) Water supply	a) Habitat supply b) Relocation c) Water supply	a) Habitat supply b) Relocation c) Water supply	a) Habitat supply b) Water supply	a) Habitat supply b) Water supply
11	a) Convection b) Weathering	a) Deposition b) Phase transition c) Weathering	a) Element supply b) Food supply c) Light-related processes d) Stimulation/inhibition	a) Element supply b) Food supply c) Habitat supply d) Stimulation/inhibition	a) Element supply b) Food supply c) Stimulation/inhibition	a) Element supply b) Stimulation/inhibition	a) Element supply b) Stimulation/inhibition	a) Stimulation/inhibition
12	a) Convection	a) Reactions	a) Element supply b) Stimulation/inhibition	a) Element supply	a) Element supply	a) Element supply	a) Element supply	a) Deposition b) Element supply c) Stimulation/inhibition
13	a) Convection b) Weathering	a) Physical properties change b) Weathering	a) Stimulation/inhibition	a) Stimulation/inhibition	a) Stimulation/inhibition	a) Stimulation/inhibition	a) Stimulation/inhibition	a) Stimulation/inhibition
14	a) Radionuclide release	a) Deposition b) Irradiation	a) Exposure	a) Exposure	a) Exposure	a) Exposure	a) Exposure	a) Exposure
15	a) Change in rock surface location	a) Change in rock surface location b) Import c) Saturation d) Terrestrialisation	a) Import b) Light-related processes	a) Import	a) Import	a) Import	a) Import	a) Import

Figure 4-1. *The general biosphere IM.*

9	10	11	12	13	14	15
a) Convection	a) Convection	a) Convection	a) Convection	a) Convection	a) Radionuclide release	
a) Convection b) Thresholding	a) Acceleration b) Convection b) Thresholding	a) Phase transitions b) Reactions c) Resuspension d) Sorption/desorption	a) Reactions	a) Convection b) Heat storage c) Light-related processes d) Pressure change	a) Phase transition b) Sorption/desorption	a) Export b) Thresholding
a) Excretion b) Uptake	a) Acceleration b) Covering c) Excretion d) Interception e) Uptake	a) Death b) Excretion c) Particle release/trapping d) Uptake	a) Acceleration b) Excretion c) Particle releas/trapping d) Uptake	a) Convection b) Light-related processes c) Reactions	a) Excretion b) Growth c) Sorption/desorption d) Uptake	a) Export
a) Decomposition b) Excretion c)Uptake	a) Acceleration b) Decomposition c) Excretion d) Movement e) Uptake	a) Consumption b) Death c) Decomposition d) Excretion e) Particle release/trapping f) Uptake	a) Excretion b) Uptake	a) Convection b) Light-related processes c) Reactions	a) Excretion b) Growth c) Sorption/desorption d) Uptake	a) Export
	a) Acceleration b) Excretion c) Movement d) Uptake	a) Death b) Excretion c) Particle release/trapping d) Uptake	a) Excretion b) Uptake	a) Convection b) Light-related processes c) Reactions	a) Excretion b) Growth c) Sorption/desorption d) Uptake	a) Export
	a) Acceleration b) Excretion c) Movement d) Uptake	a) Death b) Excretion c) Particle release/trapping d) Uptake	a) Excretion b) Particle release/trapping c) Uptake	a) Convection b) Light-relaetd processes c) Reactions	a) Excretion b) Growth c) Sorption/desorption d) Uptake	a) Export
	a) Excretion b) Movement c) Uptake	a) Death b) Excretion c) Particle release/trapping d) Uptake	a) Excretion b) Particle release/trapping c) Uptake	a) Convection b) Light-related processes c) Reactions	a) Excretion b) Growth c) Sorption/desorption d) Uptake	a) Export
a) Uptake c) Water use	a) Acceleration b) Antropogenic release c) Covering d) Excretion e) Movement f) Uptake g) Water use	a) Anthropogenic release b) Death c) Excretion d) Uptake e) Water use	a) Acceleration b) Anthropogenic release c) Excretion d) Uptake	a) Anthropogenic release b) Convection c) Light-related processes d) Reactions	a) Anthropogenic release b) Excretion c) Growth d) Sorption/desorption e) Uptake	a) Export
Water in regolith	a) Convection	a) Convection b) Physical properties change c) Relocation	a) Phase transition	a) Convection b) Heat storage	a) Convection	a) Export
a) Convection	**Surface water**	a) Convection b) Physical properties change	a) Phase transition b) Relocation c) Resuspension	a) Change of pressure b) Convection c) Heat storage d) Light related processes	a) Convection	a) Export b) Import
a) Convection	a) Convection	**Water composition**	a) Phase transition b) Relocation c) Resuspension	a) Change of pressure b) Light-related processes c) Reactions	a) Phase transition b) Sorption/desorption	a) Export
a) Convection b) Phase transitions	a) Convection b) Deposition c) Phase transitions d) Wind stress	a) Deposition b) Phase transitions c) Wind stress	**Local atmosphere**	a) Change of pressure b) Convection c) Heat storage d) Phase transitions e) Light-related processes f) Reactions	a) Convection b) Sorption/desorption	a) Export
a) Phase transitions	a) Convection b) Phase transitions	a) Convection b) Physical properties change c) Reactions	a) Change of pressure b) Convection c) Phase transition	**Temperature**	a) Reactions b) Phase transitions	a) Export
		a) Decay b) Radiolysis c) Reactions	a) Phase transition	a) Decay	**Radionuclides (*)**	a) Export
a) Import	a) Convections b) Import c) Sea level change d) Terrestrialisation	a) Import	a) Import b) Reactions	a) Import b) Light-related processes	a) Import	**External conditions**

5 Diagonal elements

The biosphere IM contains a total of 15 diagonal elements, two of which are boundary conditions occurring outside the ecosystem in question.

The identified components primarily represent different environmental media (geosphere, regolith, water in regolith, surface water, and atmosphere) and organism groups that are exposed directly or indirectly through these media (primary producers, decomposers, herbivores, carnivores, and humans). In addition water chemistry, released radionuclides, temperature and external conditions were also included as distinct components in order to increase matrix resolution and to make the IM more useful for radionuclide pathway analysis. It is possible to include temperature in each diagonal element and water composition could be included in soil water and surface water. However, that would lead to many process interactions occuring within diagonal elements and the IM would not sufficiently illustrate important radionuclide pathways. The biota (with the exception of filter feeders) are conceptually divided according to feeding preferences (decomposer, herbivore, carnivore etc.). Abiotic components (with the exception of water composition) are spatially divided (e.g. regolith, water in regolith, surface water), and there is also a diagonal element (temperature) which is a property.

The division into different components was done by experts from several fields of expertise (see Table 1-1). Due to the complexity of ecosystems, different authors sometimes subdivide the biosphere differently than is done here. The definitions in this report should therefore be regarded as SKB's own and may differ somewhat from those in the literature. In the text below, references to literature are made where appropriate. The description of diagonal elements in the following text is general and thus applicable to all kinds of ecosystems.

5.1 Geosphere

Geosphere includes the rock surrounding the repository. It also includes deep groundwater present in the saturated zone in the bedrock, ventilation shafts, gas and grout injected into fractures in the rock during construction of the repository to prevent water inflow to tunnels and other repository cavities. In literature, geosphere is often defined as the densest part of the Earth, consisting mostly of rock and regolith /Skinner and Porter 2000/. Here, regolith is treated as a separate diagonal element (see below). 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. Rock outcrops are in SKB definition part of the regolith. The components of the geosphere a further described and defined in /SKB 2001, 2010a/.

5.2 Regolith

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/. The regolith covers almost the Earth's entire surface and in SKB definition the surface of rock outcrops are included. Topography, i.e. the relief and form of the land is included as the geometric extent, i.e. position (x,y,z) of 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 far future deposits. The term overburden is used by other organisations (e.g. Posiva) for a similar feature /Posiva 2005, Lahdenperä 2005/.

5.3 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 biomass growth. Primary producers include green plants, algae and autotrophic bacteria (e.g. /Campbell 1993, Maier et al. 2009/). The diagonal element includes species, quantity (i.e. biomass) and geometry of primary producers. The geometry of primary producers can affect wind velocities and gas exchange in terrestrial areas, and can serve as a substrate for other organisms.

5.4 Decomposers

Decomposers are organisms (bacteria, fungi or animals) that feed on dead plant and animal matter and break down complex energy rich 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/. The diagonal element includes species and quantity (i.e. biomass) of decomposers.

5.5 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 although they conceptually are a mix of decomposers, herbivores, and carnivores. The diagonal element includes species, quantity (i.e. biomass) and geometry of filter feeders. The geometry of filter feeders can affect water velocities, and they can serve as substrate for other organisms.

5.6 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). The diagonal element includes species and quantity (i.e. biomass) of herbivores.

5.7 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 below). The diagonal element includes species and quantity (i.e. biomass) of carnivores.

5.8 Humans

Humans are defined as all human beings living in the affected area. This diagonal element includes the number of persons but also their activities in the modelled area.

5.9 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. This diagonal element includes the quantity of water in regolith, whereas the chemical composition of the water is treated as water composition. Water in regolith does not include the water in the bedrock as this is handled in the geosphere matrix. However, in practice they are modelled together. 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/.

5.10 Surface water

Surface water is defined here as water on the Earth's surface, collecting on the ground or in streams, rivers, lakes, open water wetlands or oceans, as opposed to water in rock, regolith or atmosphere /Heath 1987/. Atmospheric water belongs to gas and local atmosphere in the matrix, in contrast to the classification made by some other authors, e.g. /Watson and Burnett 1993/ who include rain, fog and snow in surface water. 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 the quantity of surface water, while the chemical composition of the water is treated as water composition.

5.11 Water composition

Here, water composition comprises dissolved elements and compounds, colloids and suspended particles (including dead organic matter) in surface water and water in regolith. The content of ions and elements determines e.g. pH-values, salinity, and nutrient concentrations. Thus, water composition is important for the presence of biotic components in aquatic ecosystems. Various transport, chemical and biological processes affect water composition (e.g. /Stumm 2004/).

5.12 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. 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. Gas bubbles in water are included in this diagonal element, whereas dissolved gases are treated in water composition.

5.13 Temperature

Temperature is the unique physical property that determines the direction of heat flow between two objects placed in thermal contact /Pitt 1977/. Here, 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 belong to this diagonal element, whereas large-scale climate systems belong to external factors.

5.14 Radionuclides

This diagonal element includes radionuclides in all physical and biological components of the biosphere system in question (i.e. in all physical diagonal elements such as geosphere, regolith, biota, and water).

5.15 External conditions

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

6 Processes in the Biosphere

In all, 51 processes were identified (Table 6-1). To easier illustrate different kinds of processes acting in the biosphere, 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 6) Landscape development processes. Synonyms and sub-processes (some processes are composed of several sub-processes) are listed in Appendix A along with a reference to the process in this report which they are associated with. In the text below, processes are defined and examples of how the processes act in the biosphere are described.

Table 6-1. Processes in the biosphere interaction matrix 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 6) Landscape development processes. * denotes processes that, although primarily associated with interactions involving non-human biota, may also involve humans. Full definitions are provided in sections 6.1 to 6.6. In the right column is a reference to where in the interaction matrix (Figure 4-1) the processes are located.

Process	Definition	Interactions in the matrix (is read row:column)
Biolgical processes		
Bioturbation	The mixing of elements and particles in both aquatic and terrestrial regolith by organisms.	3:2, 4:2, 5:2, 6:2, 7:2
Consumption*	When organisms feed on solid material and/or on other organisms.	4:2, 4:11, 5:3, 5:4, 5:5, 5:6, 5:7, 6:3, 7:4, 7:5, 7:6, 7:7, 7:8, 8:3, 8:4, 8:5, 8:6, 8:7
Death*	The generation of dead organic matter by organisms, including losses of parts as well as death of entire organisms.	3:2, 3:11, 4:2, 4:11, 5:2, 5:11, 6:2, 6:11, 7:2, 7:11, 8:2, 8:11
Decomposition	The breakdown of organic matter by organisms.	4:2, 4:9, 4:10, 4:11
Excretion*	The excretion of water or elements to the surrounding media by humans and other organisms.	3:9, 3:10, 3:11, 3:12, 3:14, 4:9, 4:10, 4:11, 4:12, 4:14, 5:10, 5:11, 5:12, 5:14, 6:10, 6:11, 6:12, 6:14, 7:10, 7:11, 7:12, 7:14, 8:10, 8:11, 8:12, 8:14
Food supply	The fraction of produced biomass and particulate matter that can be used as a food source for humans and other organisms.	2:4, 2:8, 3:5, 3:6, 3:8, 4:5, 4:7, 4:8, 5:5, 5:7, 5:8, 6:5, 6:7, 6:8, 7:5, 7:7, 7:8, 8:7, 11:3, 11:4, 11:5
Growth*	The generation of biomass by organisms	3:14, 4:14, 5:14, 6:14, 7:14, 8:14
Habitat supply	The providing of habitat for organisms by abiotic structures or other organisms.	2:3, 2:4, 2:5, 2:6, 2:7, 2:8, 3:3, 3:4, 3:5, 3:6, 5:3, 5:4, 9:3, 9:4, 10:3, 10:4, 10:5, 10:6, 10:7, 10:8, 11:4
Intrusion	Non-human organisms or humans enter the repository, for example by locomotion, drilling or growth.	3:1, 4:1, 5:1, 6:1, 7:1, 8:1
Material supply	The amount of material that is available for human utilisation for purposes other than feeding.	1:8, 2:8, 3:8, 4:8, 5:8, 6:8, 7:8
Movement*	Animal locomotion in surface water.	4:10, 5:10, 6:10, 7:10, 8:10
Particle release/trapping*	Organisms release particles (for example by fragmentation, spawning and pollen release) or trap particles (for example with gills, feathers and slime)	3:11, 3:12, 4:11, 5:11 6:11, 6:12, 7:11, 7:12
Primary production	The fixation of carbon by primary producers in photosynthesis.	3:3

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 model areas. Stimulation and inhibition due to consumption or arterial use is dressed in separate processes.	3:3, 3:4, 3:5, 3:6, 3:7, 3:8, 4:3, 4:4, 4:5, 4:6, 4:7, 4:8, 5:3, 5:4, 5:5, 5:6, 5:7, 5:8, 6:3, 6:4, 6:5, 6.6, 6:7, 6:8, 7:3, 7:4, 7:5, 7:6, 7:7, 7:8, 8:3, 8:4, 8:5, 8:6, 8:7, 8:8, 11:3, 11:4, 11:5, 11:6, 11:7, 11:8, 12:3, 12:8, 13:3, 13:4, 13.5, 13.6, 13:7, 13:8
Uptake*	The incorporation of water or elements from the surrounding media into humans and other organisms.	3:9, 3:10, 3:11, 3:12, 3:14, 4:9, 4:10, 4:11, 4:12, 4:14, 5:10, 5:11, 5:12, 5:14, 6:10, 6:11, 6:12, 6:14, 7:10, 7:11, 7:12, 7:14, 8:10, 8:11, 8:12, 8:14
Processes related to human behaviour		
Anthropogenic release	Release caused by humans of substances, water or energy into the local biosphere.	8:10, 8:11, 8:12, 8:13, 8:14
Material use	Human utilisation of the environment for purposes other than feeding.	8:1, 8:2, 8:3, 8:4, 8:5, 8:6, 8:7
Species introduction/ extermination	Introduction or extermination of species to or from the model domain by human activities. (e.g. introduction of crayfish in lakes).	8:3, 8:4, 8:5, 8:6, 8:7
Water use	Water use by humans for other purposes than drinking, e.g. washing, irrigation and energy production. May affect the distribution and flow of water	8:9, 8:10, 8:11
Chemical, mechanical and physical processes		
Change of pressure	Pressure change in air or water above a surface.	9:1, 10:1, 10:13, 11:13, 12:13, 13.12
Consolidation	Any process whereby loosely aggregated, soft, or liquid earth materials become firm and coherent rock.	2:1, 2:2
Element supply	The availability of elements and substances for use by organisms.	2:3, 2:4, 11:3, 11:4, 11:5, 11:6, 11:7, 12:3, 12:4, 12:5, 12:6, 12:7, 12:8
Loading	Force caused by the weight of material that affects the underlying rock.	2:1, 10:1
Phase transitions	Changes between different states of matter: solid, liquid and gas.	2:11, 2:14, 9:12, 10:12, 11:2, 11:12, 11:14, 12:9, 12:10, 12:11, 12:13, 13:9. 13:10, 13:12, 13:14, 14:12
Physical properties change	Changes in volume, density and/or viscosity.	9:11, 10:11, 13:2, 13:11
Reactions	Chemical reactions excluding weathering, decomposition and photosynthesis.	2:11, 2:12, 3:13, 4:13, 5:13, 6:13, 7:13, 8:13, 11:13, 12:2, 12:13, 13:11, 13:14, 14:11, 15:12
Sorption/desorption	Dissolved substances adhere to surfaces or are released from surfaces.	2:11, 2:14, 3:14, 4.14, 5.14, 6.14, 7:14, 8:14, 11:14, 12:14
Water supply	The amount of water available for drinking and other uses by humans and other organisms.	9:3, 9:4, 9:5, 9:6, 9:7, 9:8, 10:3, 10:4, 10:5, 10:6, 10:7, 10:8
Weathering	Disintegration of solid matter into smaller pieces.	1:2, 9:1, 10:1, 11:1, 11:2, 13:1, 13:2
Wind stress	A mechanical force generated by wind affecting the biosphere.	12:10, 12:11
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).	2:10, 3:10, 3.12, 4.10, 5.10, 6:10, 8.10, 8:12

Convection	The transport of a substance or a conserved property with a fluid or gas.	1:9, 1:10, 1:11, 1.12, 1:13, 2:9, 2:10, 2:13, 3:13, 4.13, 5:13, 6.13, 7.13, 8:13, 9:1, 9:10, 9:11, 9:13, 9:14, 10:1, 10:9, 10:11, 10:13, 10:14, 11:1, 11:9, 11:10, 12:1, 12:9, 12:10, 12:13, 12:14, 13:1, 13:10, 13:11, 13:12, 15.10
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.	3:10, 8:10
Deposition	Vertical transfer of a material or element to a surface of any kind due to gravitation, e.g. sedimentation, rainfall, and snowfall.	11:2, 12:8, 12:10, 12:11, 14:2
Export	Transport out of the model area.	2:15, 3:15, 4:15, 5:15, 6:15, 7:15, 8:15, 9:15, 10:15, 11:15, 12:15, 13:15 14:15
Import	Transport into the model area.	10:15, 15:2, 15:3, 15:4, 15:5, 15:6, 15:7, 15:8, 15:9, 15:10, 15:11, 15:12, 15:13, 15:14
Interception	The amount of precipitation that does not reach the ground but is retained on vegetation.	3:10
Relocation	Transport of solid matter and sessile organisms from one point to another.	2:3, 8:2, 9:2, 9:11, 10:2, 10:3, 10:4, 10:5, 10:6, 10:12, 11:12
Resuspension	The stirring up of previously settled particles in water or air.	2:11, 10:2, 10:12, 11:12
Saturation	Change in water content that affects physical and chemical properties of the regolith.	9:2, 15:9
Radiological and thermal processes		
Decay	The physical transformation of radionuclides to other radionuclides or stable elements.	14:11, 14:13
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.	14:3, 14:4, 14:5, 14:6, 14:7, 14:8
Heat storage	The storage of heat in solids and water.	2:13, 9:13, 10:13, 12:13
Irradiation	The process whereby an object is exposed to radiation and absorbs energy.	14:2
Light-related processes	Processes related to the light entering the biosphere (insolation), e.g. absorption, attenuation, reflection and scattering.	2:3, 2:13, 3:13, 4:13, 5:13, 6:13, 7:13, 8:13, 10:13, 11:3, 11:13, 12:13, 15:3, 15:13
Radiolysis	The disintegration of molecules caused by radionuclide decay.	14:11
Radionuclide release	Release of radionuclides from the repository for spent nuclear fuel.	1:14, 14:1
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, 15:1, 15:2
Sea level change	Alteration in the level of the sea relative to the land.	15:10
Terrestrialisation	Infilling of a lake or shallow sea basin with mire vegetation.	15:2, 15:10
Thresholding	The occurrence and location of thresholds that delimit water bodies like lakes and sea basins.	2:9, 2.10, 2.15

6.1 Biological processes

Biological processes are processes that are dependent on organisms. Species differ in their uptake and absorption of radionuclides, which affects the transport and accumulation of those radionuclides. One way of exposure to radionuclides is via intake of water and food and thus the distribution of biota and transport of radionuclides in the food web is 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 non-human biota. Processes that are strictly related to human behavior are treated in Section 6.2. The biological processes described below are processes that are assumed to influence radionuclide transport and accumulation.

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 Decomposition

Decomposition is the disintegration of dead organic matter by decomposers /Begon et al. 1996/. By means of decomposition, energy-rich molecules are broken down to carbon dioxide, water and inorganic nutrients. 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 rate of decomposition may be important, and a reduced decomposition rate results in the generation and expansion of carbon reservoirs and associated elements in the regolith, e.g. peat and sediments.

6.1.4 Death

Death is the production of dead organic matter generated by organisms. The dead organic matter may originate from 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.

6.1.5 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 is important for the transport and accumulation of radionuclides 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 a food source 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 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 the 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, 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: insolation, climate, substrate, and area of leaves and other green parts of the plants (e.g. /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 diagonal element influences another diagonal element 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 /McNaughton 1985, Steinman 1996/. Organisms may inhibit each other by e.g. toxin production, parasitism, and competition for space and resources /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 behavior

Human behavior may have large effect on the biosphere, shaping ecosystems by introducing species or elements or by disturbing or removing material in large quantities. The processes related to human behavior described below are processes that are assumed to influence radionuclide transport and accumulation.

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 diagonal 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 dose 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, Tjernberg 2001/.

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, whereas doses due to external exposure (such as washing clothes and showering) are often small (e.g. /Avila et al. 2010/).

6.3 Chemical, mechanical, and physical processes

Chemical, mechanical, and physical processes are processes that occur due to mechanical force 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 states elements are tightly bound to particles and in other states they may be easily dissolved and transported with water. Moreover, these processes can affect the bioavailability of radionuclides if the radionuclides are present in forms readily taken up by organisms. The chemical, mechanical and physical processes described below are processes that are assumed to influence radionuclide transport and accumulation.

6.3.1 Change of pressure

Pressure is the amount of force acting on an unit area /Daintith 1985/. Here pressure refers to the pressure of the air and water above a surface, 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/.

6.3.3 Element supply

This is the amount of elements and 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 glaciations 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 between 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 (see mechanical and biological 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 may have a limited effect on transport and accumulation of radionuclides, they may be important for ecosystem function and are therefore included in the IM.

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/. These processes are 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 coefficients 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 washing, industry or agriculture (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 affecting e.g. wave formation (see 'Convection'), and the quantities of water contained in sea spray (see 'Resuspension').

6.4 Transport processes

Transport processes are processes whereby elements and substances are transferred (transported) from one point to another in a system. These processes influence where in the system radionuclides end up or if the radionuclides are transported out of the system in question. The transport processes described below are processes that are assumed to influence radionuclide transport and accumulation.

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 /Pitt 1977/. 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 diagonal 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 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). Convection is important in safety assessments as it is a major process affecting the transport of radionuclides.

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 the exchange of gases and particles between the surface water and the atmosphere /Loose et al. 2009/. The quantity of primary producers covering the contact area between surface waters and the atmosphere influences the quantity of water that can evaporate, the exchange of oxygen between the atmosphere and the surface water, and surface water movements. Ice covering 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, and deposition of radionuclides and other toxicants on the surface of the 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 model area (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 substances in the model domain. Export of organisms affects the number of inhabitants in the model domain 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 model area (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 substances in the model domain. Import of organisms affects the number of inhabitants in the model area and related processes such as consumption and production.

6.4.7 Interception

In the biosphere IM, interception is used to cover all wet and dry deposition of elements that are intercepted /retained on vegetation and will not infiltrate into the ground or take part in the subsurface transport as well as runoff process (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 they are 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 is 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 Thermal and radiological processes

Thermal processes are those processes that concern temperature, solar insolation and radionuclides. The thermal and radiological processes described below are processes that are assumed to influence radionuclide transport and accumulation.

6.5.1 Decay

Decay is reduction in activity of a nuclide due to radioactive transformation /SMS TNC 1990, Choppin et al. 2002/. 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 heat that may affect the temperature in the different components of the biosphere system.

6.5.2 Exposure

Exposure is the process whereby living or dead organisms/matter are exposed to irradiation from alpha, beta, and gamma decay /SMS TNC 1990, IAEA 2007/. 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 large dose of radiation during a short period of time may cause acute radiation syndrome. Chronic exposure, even in small doses, can increase the probability of other diseases or conditions such as cancer and genetic damage.

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) /Sverdrup et al. 1942, Chapter 2 in Wetzel 2001/ and prevents extreme changes in temperature in aquatic ecosystems. In addition, the specific heat storage of water affects stratification and mixing as well as convection in lakes and oceans (e.g. /Chapter 4 in Horne and Goldman 1994, Chapter 6 in Wetzel 2001,/). Although heat capacity is lower in regolith than in water, the density and heat properties of regolith determine the amount of heat that can be stored in a volume of regolith and thereby also influence the temperature in terrestrial ecosystems.

6.5.4 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, 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/).

6.5.5 Radiolysis

Radiolysis is the disintegration of molecules caused by radiation /SMS TNC 1990/. 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/.

6.5.6 Radionuclide release

Radionuclide release is the release of radionuclides from a repository for spent nuclear fuel via the geosphere to the biosphere.

6.5.7 Irradiation

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

6.6 Landscape development processes

The type of ecosystem (marine, limnic or terrestrial) greatly influences transport and accumulation of radionuclides. Thus, processes affecting the landscape development are important to consider in safety assessments. The landscape development processes described below are processes that are assumed to influence radionuclide transport and accumulation

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 the 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 also after a change in rock surface locations. 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. However, cavern collapse would be greatly attenuated at the surface, and fault throws of more than ~0.1 m are highly unlikely at least for deep repositories /SKB 2001/.

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 '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 pace 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 are presented for the Forsmark area in mid-Sweden by /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 Terrestrialisation

Terrestrialisation is succession from an open water basin to a mire /Korhola and Tolonen 1996, Rydin and Jeglum 2006/. Conceptually, terrestrialisation is a mix of several other processes (e.g. thresholdning, sea level, change in rock surface location, deposition and primary production), but in the IM resolution, this process leads to a transition from one ecosystem matrix (limnic or marine IM) to another (terrestrial IM). Terrestrialisation is important to model and is, therefore, treated as a separate process. One path leading to terrestrialisation in deepwater lakes or marine basins is the sedimentation of material to the floor of the lake or sea. Eventually, the water becomes shallow enough to enable emergent marsh vegetation to grow and build up peat, permitting a transition to a fen or bog /Reid 1976, Brunberg and Blomqvist 2000/. Terrestrialisation may also occur due to peatland succession, where a cover of mosses, together with floating and half-rooted vegetation, produces a peat mass that gradually develops from the edges towards the middle of a lake /Rydin and Jeglum 2006, Mitsch and Gosselink 2007/. The main processes leading to terrestrialisation are primary production (mire growth) and deposition (sedimenting material), but there are also other factors that promote or inhibit terrestrialisation such as resuspension, relocation, wind (acceleration), consumption and water composition. Terrestrialisation affects the regolith by affecting the morphometry of the lake/marine basin as well as the terrestrial area.

6.6.4 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 sea, determines lake volume etc.

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Appendix A

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 general biosphere IM**	**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
Degassing	Phase transitions	Chemical, mechanical and physical processes
Degradation	Reaction	Chemical, mechanical and physical processes
Dehydration	Excluded	Irrelevant process in a radionuclide perspective

Process name (previously used by SKB or commonly used in the literature)	Process name in the general biosphere IM	Group of processes
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
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 behavior
Farming	Species introduction/extermination	Processes related to human behavior
Feeding	Consumption	Biological processes
Fermentation	Decomposition	Biological processes
Fertilizing	Anthropogenic release	Processes related to human behavior
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

Process name (previously used by SKB or commonly used in the literature)	Process name in the general biosphere IM	Group of 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	Terrestrialisation	Landscape development processes
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 behavior
Isostatic adjustment	Change in rock surface location	Landscape development preocesses
Kinetics	Reactions	Chemical, mechanical and physical processes
Lake infilling	Terrestrialisation	Landscape development processes
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 behavior
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
Non-biological decomposition	Reactions	Chemical, mechanical and physical processes
Oxidation	Reactions	Chemical, mechanical and physical processes

Process name (previously used by SKB or commonly used in the literature)	Process name in the general biosphere IM	Group of 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

Process name (previously used by SKB or commonly used in the literature)	Process name in the general biosphere IM	Group of 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 behavior
Water extraction	Water use	Processes related to human behavior
Water flow	Convection	Transport processes
Water flux	Convection	Transport processes
Water pumping	Water use	Processes related to human behavior
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