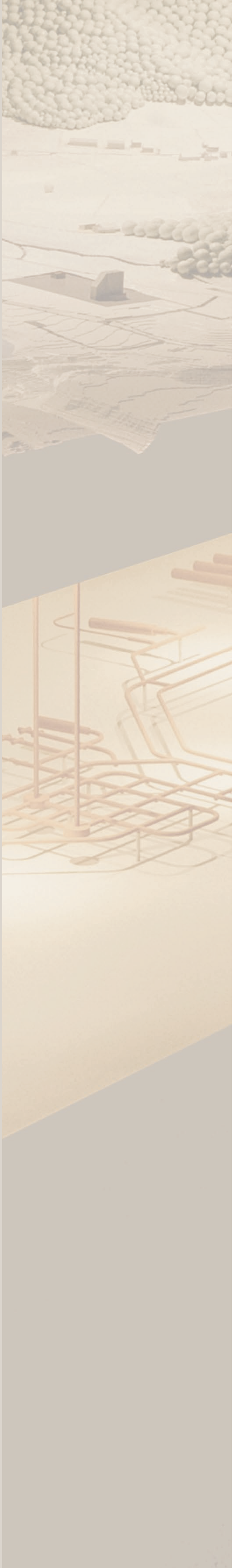

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ARBEITSBERICHT NAB 24-06

Post-Closure Biosphere Assessment

August 2024

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KEYWORDS
Biosphere, biosphere assessment, biosphere modelling, deep geological repository, post-closure safety, radiological consequences, general licence application, RBG, safety assessment, safety case, SwiBAC

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Nagra Arbeitsberichte ("Working Reports") present the results of work in progress that have not necessarily been subject to a comprehensive review. They are intended to provide rapid dissemination of current information.

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Abstract

Nagra, the National Cooperative for the Disposal of Radioactive Waste, is responsible for the development and safe implementation of a deep geological repository for radioactive waste in Switzerland. The concept involves the disposal of low-, intermediate-, and high-level waste in a deep geological repository within a clay-rock formation (Opalinus Clay) at a depth of over 800 m. The disposed waste inventory will remain hazardous for a long time after closure, and some radionuclides can potentially reach the biosphere over extremely long timescales.

The longevity of the waste means that there is potential for some radionuclides from, or ingrown from, the disposed inventory to reach the surface through the groundwater in the very long term (tens of thousands to hundreds of thousands of years in the future). Dose assessment is required to evaluate potential exposure to humans arising from such releases and to meet regulatory guidelines and requirements. Modelling of radionuclide behaviour at the surface and near-surface (collectively referred to as the biosphere in this context) is needed to evaluate potential doses. The biosphere modelling, therefore, provides a measure of the performance of Nagra's repository system, as well as a quantitative measure of radiological safety, through dose calculations.

This report fully describes the basis for Nagra's biosphere modelling in support of the general licence application. Nagra's approach to representing the biosphere has remained consistent throughout the site selection process, while being maintained in response to new understanding and updated sources of information. A systematic approach is used in developing, justifying and documenting Nagra's approach to the biosphere assessment, consistent with the latest international guidance:

- documenting the context for the biosphere modelling;
- identifying the biosphere systems relevant to the assessment, with a description of the reference and alternative biospheres;
- presenting conceptual and mathematical models of radionuclide migration and potential exposure, and supporting these with data;
- implementing the models and data in a compartment modelling framework and encoding them within Nagra's Swiss Biosphere Assessment Code (SwiBAC) software;
- using SwiBAC to calculate potential doses (Sv a^{-1}) at equilibrium for a constant unit release of radionuclides (Bq a^{-1}) in groundwater to the biosphere (termed biosphere dose conversion factors, BDCFs); and
- using deterministic sensitivity calculations to explore alternative assumptions, and using probabilistic sensitivity calculations to identify further important processes and parameters.

Reference biosphere dose conversion factors are based on potential radionuclide releases to a valley based on present-day conditions in Northern Switzerland, which allows for the assessment of a comprehensive range of exposure pathways. The modelling aims to be realistic in terms of representing radionuclide migration in the biosphere, but pessimistic in evaluating potential doses. The latter is achieved by assuming the presence of humans in the vicinity of the release area and that they make reasonable maximum use of local resources by spending all of their time in this area, drawing local groundwater and leading a self-sufficient lifestyle.

Alternative biosphere conditions are also explored. A warmer-drier climate would result in biosphere dose conversion factors that are higher than those for a present-day climate due to lower water flows in the biosphere and higher irrigation requirements. On average, the biosphere dose conversion factors increase by a factor of three whereas, for a small number of radionuclides, the

increase can be up to about a factor of ten. Conversely, releases to an area drained for farming and releases under cold climate conditions (given that the timescale will include glacial-interglacial cycles) result in biosphere dose conversion factors that are below those of the reference biosphere.

Sensitivity calculations demonstrate the importance of local characteristics in determining biosphere dose conversion factors, especially the size of the valley system and the receptor. For example, radionuclide releases directly into a river result in biosphere dose conversion factors that are typically several orders of magnitude lower than the reference biosphere, which assumes direct releases into a shallow local aquifer.

Probabilistic sensitivity calculations highlight the importance of sorption/retention of radionuclides within the shallow local aquifer, and of transfer factors through the agricultural food chain. The representation of these processes has been subject to review in preparation for the general licence application assessment.

The biosphere dose conversion factors provide a means for Nagra's consequence analyses to evaluate potential doses associated with radionuclide releases from the geosphere. Uncertainty concerning the biosphere on long timescales is unavoidable; nonetheless, the reference biosphere dose conversion factors are shown to provide a generally pessimistic assessment.

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List of Acronyms

ATW	Alpha-toxic waste
BDCF	Biosphere dose conversion factor
BIOMASS	Biosphere modelling and assessment
BIOMOVS	Biospheric model validation study
ENDF	Evaluated nuclear data file
ENSI	Swiss Federal Nuclear Safety Inspectorate (*Eidgenössisches Nuklearsicherheitsinspektorat*)
FEP	Features, events and processes
FOEN	Federal Office for the Environment
HLW	High-level waste (spent fuel assemblies and high-level waste from reprocessing)
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
JO	Jura Ost
KEG	Nuclear Energy Act (*Kernenergiegesetz*)
L/ILW	Low- / intermediate-level waste
NAB	Nagra Work Report (*Nagra Arbeitsbericht*)
NAQUA	National groundwater monitoring network
NL	Nördlich Lägern
NTB	Nagra Technical Report (*Nagra Technischer Bericht*)
RBG	General licence application (*Rahmenbewilligungsgesuch*)
RPO	Radiological Protection Ordinance (*Strahlenschutzverordnung*)
SGT	Sectoral Plan for Deep Geological Repositories (*Sachplan geologische Tiefenlager*)
SGT-E1	Stage 1 (of the Sectoral Plan for Deep Geological Repositories)
SGT-E2	Stage 2 (of the Sectoral Plan for Deep Geological Repositories)
SGT-E3	Stage 3 (of the Sectoral Plan for Deep Geological Repositories)
SSR	Specific Safety Requirements (IAEA safety standard)
SwiBAC	Swiss Biosphere Assessment Code
TAME	Terrestrial-Aquatic Model of the Environment
TF	Transfer factor
WENRA	Western European Nuclear Regulators Association
ZNO	Zürich Nordost

1 Introduction

1.1 Context

In Switzerland, legal regulations (Nuclear Energy Act (KEG 2003) and Nuclear Energy Ordinance (KEV 2004) and guidelines are in place for the management of radioactive waste. The Nuclear Energy Ordinance (KEV) classifies Switzerland's radioactive waste into low- and intermediate-level waste (L/ILW), alpha-toxic waste[1] (ATW) and high-level waste (HLW), the latter comprising spent fuel (SF) and vitrified HLW from reprocessing (RP-HLW). The Nuclear Energy Act (KEG) requires the disposal of all these types of radioactive waste in deep geological repositories. The feasibility of this disposal solution has been demonstrated for L/ILW in Nagra (1985) and for long-lived intermediate-level waste and HLW in Nagra (2002b).

The Sectoral Plan for Deep Geological Repositories (SGT) regulates the search for suitable siting regions for deep geological repositories in Switzerland. This site selection process is conducted in three stages (BFE 2008). Stages 1 and 2 have already been completed and Nagra is currently in Stage 3 (SGT-E3). Clarifications on the safety-related specifications for this stage are provided in ENSI 33/649 (ENSI 2018), while ENSI Guideline G03 and the corresponding explanatory report (ENSI 2023, ENSI 2020) specify the protection objective, protection criteria and design principles for deep geological repositories.

In SGT-E3, three siting regions located in Northern Switzerland have been considered – Jura Ost (JO), Nördlich Lägern (NL) and Zürich Nordost (ZNO) – with the objective of selecting one siting region for an HLW repository, one for an L/ILW repository, or one for a combined repository for all waste types.

Following a comparison of these siting regions, Nagra concluded that NL is the safest and most flexible siting region and is therefore applying for a general licence for a combined repository for both HLW and L/ILW at the Haberstal site.

The justification for this selection and the safety demonstration for a repository at the site are submitted as part of the general licence application (RBG[2]). The reports relating to post-closure safety, shown in Fig. 1-1, are structured as follows:

- The overall safety-related argumentation, including post-closure and operational safety, is summarised in an overarching safety report ("*Sicherheitsbericht*") NTB 24-01 (Nagra 2025b) shown at the top of .
- The upper left side of Fig. 1-1 shows the reports supporting Nagra's site comparison. The available options are compared with respect to safety and technical feasibility and the results are synthesised in NTB 24-03 (Nagra 2025a) ("*Bericht zur Begründung der Standortwahl*").
- The upper right side of Fig. 1-1 shows the reports documenting the post-closure safety case for the combined repository at the site, including its synthesis in the post-closure safety report NTB 24-10 (Nagra 2024f).
- The lower part of Fig. 1-1 shows a report that presents the safety and repository concept, including the provisional design, and reports providing the assessment basis.

[1] According to Nagra (2024a), ATW can coexist with L/ILW within the same emplacement caverns. As a result, for the sake of simplicity, the term L/ILW encompasses ATW without explicit mention.

[2] From the German *Rahmenbewilligungsgesuch*.

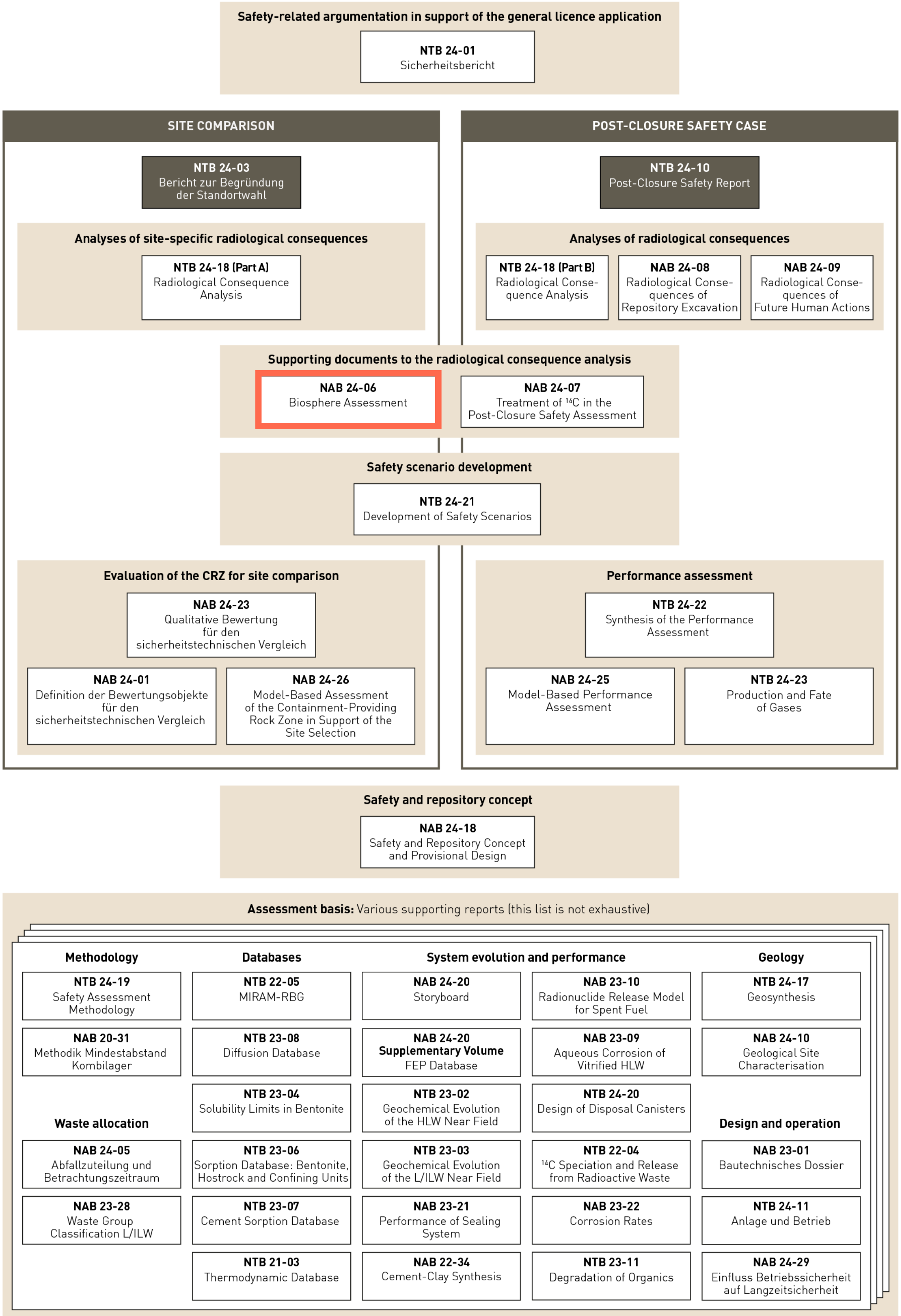

Fig. 1-1: Structure of reports covering post-closure safety aspects of the site comparison and the post-closure safety case

The present report is bordered in red in Fig. 1-1 and is part of the supporting documents to the radiological consequence analysis, supporting both the site comparison and the post-closure safety case for the combined repository at the site.

1.2 Scope of the present report

The inventory to be disposed of within the deep geological repository will remain hazardous for a long time after closure and a small fraction of the radionuclides originating or ingrown from the disposed waste can potentially reach the surface and near-surface environment (referred to as the biosphere) over extremely long timescales. Modelling of radionuclide behaviour and potential exposures after releases to the biosphere is needed to demonstrate the performance of the repository system; the biosphere itself does not provide a safety function.

The timescales involved and the dynamic nature of the biosphere mean that there is significant uncertainty about the nature of the surface environment into which radionuclide releases might occur in the distant future. Given these uncertainties, the biosphere modelling aims to deliver an overall pessimistic[3] assessment to help ensure that potential dose consequences to humans who might be present are not underestimated. Consistent with regulatory requirements, evaluation of potential doses to humans is taken to provide an overall measure of environmental safety.

This report supports the calculations for the site selection and the safety case by defining so-called biosphere dose conversion factors (BDCFs). BDCFs are used as part of the radiological consequence analysis (Nagra 2024g) to convert the radionuclide-specific release rates from the geosphere into the annual individual dose rates with the aim of comparing them to the criteria defined in regulations.

The biosphere model developed in this report (as described in Chapter 4) also serves as a basis for the assessment of the radiological consequences of repository excavation by erosive processes (Nagra 2024h) and the radiological consequences of future human actions (Nagra 2024i).

The concepts and the data used in this report are consistent with Nagra's assessment of the future hydrogeological, long-term evolution and climate evolution (Nagra 2024d, Nagra 2024e, Nagra 2024c, Nagra 2024b).

1.3 Historical and international context

ENSI guidelines on assessing the safety of geological disposal (ENSI 2023, ENSI 2020) and Nagra's approach to modelling the biosphere draw upon guidelines from international organisations including the International Commission on Radiological Protection (ICRP), the International Atomic Energy Agency (IAEA) and the Western European Nuclear Regulators Association (WENRA). In particular, the ICRP provides a framework for radiological protection in ICRP (2007) and guidelines specific to the deep geological disposal of radioactive waste in ICRP (2013).

Nagra's approach to biosphere modelling has been established and refined over thirty years through iterative assessments. Its approach to modelling the biosphere in post-closure safety assessments is based on the assessment developed in support of Project Opalinus Clay (Nagra 2002b). This approach was developed during the 1990s and was called the Terrestrial-Aquatic Model of the Environment (TAME) (Klos et al. 1996, Nagra 2002a). In preparation for assessments in support of initial safety analyses for Stage 1 of the Sectoral Plan (SGT-E1), the biosphere model was reviewed in Brennwald & van Dorp (2008). This model was used to support the radiological consequence analysis in SGT-E1 (Nagra 2008). Biosphere modelling carried out in

[3] The term "pessimistic" is used in this report to refer to assumptions or parameter values which are possible, but lead to results less favourable than the reality or the most likely outcome.

the context of the provisional safety assessment for SGT-E2 was described in Nagra (2010). This was followed by a review of element-dependent biosphere parameters (apart from sorption coefficients) and an update of the model to use new data compilations (Walke et al. 2013a). The biosphere modelling for further analyses for SGT-E2 is described in Nagra (2014). Sorption properties for biosphere materials have been subject to a full, systematic review and updated in preparation for the RBG assessment and are described in Metcalfe et al. (2023).

During this period, Nagra has participated in international collaborative efforts to develop and refine guidance on biosphere assessment, including development of a reference biosphere methodology through the international collaborative BIOMOVS II programme (BIOMOVS II 1996), which laid the foundation for IAEA guidelines referred to as the BIOMASS methodology (IAEA 2003). The IAEA recently coordinated a working group to enhance the original BIOMASS methodology (Lindborg et al. 2022), through Phase 2 of their MODARIA programme[4], with support from the international collaborative BIOPROTA forum[5]. The enhanced BIOMASS methodology, therefore, has been established from experience gained from several national geological disposal programmes over the past twenty years and more and provides the basis for Nagra's model of the biosphere for SGT-E3.

1.4 Structure of this report

The structure of this report is consistent with the enhanced BIOMASS methodology (Lindborg et al. 2022). The aim is to provide a complete and transparent description and justification for the way in which the biosphere is considered in the context of the RBG safety assessment, and with reference to supporting evidence.

- Biosphere assessment should be developed and understood in the context within which it is undertaken, such that a clear definition of the assessment context forms a cornerstone of the approach. This is documented in Chapter 2.
- Given the context, including the extremely long timescales for potential radionuclide releases, the next step of the methodology is to identify how the biosphere should be modelled, including a definition of reference and alternative cases; this is done in Chapter 3.
- Conceptual and mathematical models for the biosphere cases are then described in Chapter 4, and associated data are collated and justified in Chapter 5.
- Results for reference, alterative and systematic sensitivity analyses are presented in Chapter 6, along with an introduction to the SwiBAC software tool, which implements Nagra's approach for representing the biosphere.
- Chapter 7 provides a summary and conclusions.
- References are given in Chapter 8.

[4] www-ns.iaea.org/projects/modaria/modaria2.asp (retrieved 29.02.2024)

[5] www.bioprota.org (retrieved 29.02.2024)

2 Definition of the assessment context

Biosphere modelling is undertaken within the framework of the post-closure safety assessment, which supports the safety case for geological disposal. The context for biosphere assessment in support of the RBG is provided in this chapter including referencing to ENSI guidelines (ENSI 2018, ENSI 2023, ENSI 2020). The original ENSI guidelines were written in German. While an English translation exists for most of them, it is provided for information purposes only and has no legal force. For this reason, this chapter quotes the original German text of the guidelines and provides an English translation immediately below.

Nagra's model concepts and data for biosphere assessment in support of SGT-E2 were examined by ENSI and its experts (ENSI 2017). In general, the specific requirements in SGT-E2 concerning exfiltration areas, climate variants, the reference biosphere, site-specific biosphere models and the dynamics of carbon in the biosphere were fulfilled by Nagra. Therefore, the work from SGT-E2 provides a basis for the work in the context of the documentation of the RBG.

Understanding the context helps to ensure that the assumptions necessary for making projections of biosphere conditions over long timescales are relevant and that uncertainties are managed and understood. Topics covered in describing the context for biosphere assessment are drawn from the enhanced BIOMASS methodology (Lindborg et al. 2022) and reflected in the subsections below.

2.1 Purpose of the assessment

The purpose of Nagra's biosphere modelling is to provide a means for evaluating the radiological significance of calculated radionuclide releases from the deep geological repository in the very long term, as part of the demonstration of the safety of the repository and the resulting protection of humans and the environment.

ENSI G03 (ENSI 2023), Art. 4.1:

Mit der geologischen Tiefenlagerung sind radioaktive Abfälle so zu entsorgen, dass der Schutz von Mensch und Umwelt vor deren ionisierender Strahlung dauerhaft gewährleistet ist, ohne dass künftigen Generationen unzumutbare Lasten und Verpflichtungen auferlegt werden.

Deep geological disposal of radioactive waste has to ensure the long-term protection of humans and the environment from the effects of ionising radiation, without imposing undue burdens and obligations on future generations.

Consistent with ENSI guidelines, radiological significance is evaluated by assessing potential doses to humans. Given uncertainty in making projections about biosphere conditions in the very long term, the assessment is made on a generally pessimistic basis by assessing potential doses to individuals representative of the most affected population group. This group is defined as making reasonable maximum use of local resources through a self-sufficient lifestyle. To help avoid undue pessimism, the behaviours of the population group(s) aim to be realistic and credible, based on present-day behaviours relevant to the local and climatic conditions assumed (see also Section 2.7).

The objective is to provide confidence that the repository system is sufficiently protective of humans and the environment by assessing a range of credible conditions that err on the side of pessimism (i.e. helping to ensure that potential radiological consequences are not underestimated).

ENSI G03, Art. 9.3.3 b:

[...]

Für die Berechnung der Strahlendosis ist ein repräsentatives Individuum innerhalb der von den potenziellen Auswirkungen eines geologischen Tiefenlagers meist betroffenen Bevölkerungsgruppe mit aus heutiger Sicht realistischen Lebensgewohnheiten zu postulieren. Bei der Analyse ist zu unterstellen:

1. Mögliche Varianten der Klimaentwicklung und entsprechende Biosphärenmodelle sind festzulegen und ihre Bedeutung für die Langzeitsicherheit des geologischen Tiefenlagers ist zu untersuchen.

2. Die Wirkung ionisierender Strahlung auf den Menschen hat sich nach den heutigen Kenntnissen zu richten.

[...]

[…]

When calculating the radiation dose, assumptions have to be based on a representative individual from the population group most affected by the potential impact of a deep geological repository, with realistic living habits based on a present-day perspective. The analysis has to assume the following:

1. Possible climate change variants and associated biosphere models have to be defined and their significance for the long-term safety of the deep geological repository investigated.

2. The effect of ionising radiation on humans has to be based on current knowledge.

[…]

ENSI Explanatory Report for Guideline G03 (ENSI 2020), Art. 9.3.3 b:

Die Dosisberechnung stützt sich unter anderem auf Annahmen über die Strahlungsempfindlichkeit und die Lebensweise von Menschen, die in weit entfernter Zukunft leben. Die Richtlinie fordert, dass aus heutiger Sicht glaubwürdige Annahmen zu treffen sind. Damit ist gemeint, dass ausgehend von mutmasslichen örtlichen und klimatischen Gegebenheiten eine für heutige Menschen mögliche Besiedlung und Lebensweise (inklusive Selbstversorger) anzunehmen ist. Die Ergebnisse der Individualdosis-Berechnung dienen der Bewertung der Freisetzung der radioaktiven Stoffe aus dem geologischen Tiefenlager und somit der Bewertung der in der Zukunft vorhandenen Schutzfunktion des geologischen Tiefenlagers. [...]

Amongst other things, the dose calculation is based on assumptions about radiation sensitivity and human lifestyles in the distant future. The guideline requires that the assumptions made are credible from today's perspective. This means that, based on the presumed local and climatic conditions, the possibility of a settlement and human lifestyle (including self-sufficiency) similar to present-day humans should be assumed. The results of the individual dose calculation are used to evaluate the release of radioactive substances from the deep geological repository and thus to evaluate the future protection function of the deep geological repository. […]

The present-day biosphere in Northern Switzerland is used as an analogue for conditions that might arise in the future over the period under consideration (see Section 2.6 on time frames). A range of alternative biosphere conditions is considered to envelope uncertainty about geomorphological and climatic conditions in line with ENSI 33/649 and ENSI G03. Understanding of the robustness of conclusions is also informed through systematic sensitivity analysis.

ENSI 33/649 (ENSI 2018):

Gemäss den Vorgaben der Richtlinie ENSI-G03 und den im Folgenden beschriebenen Präzisierungen und Ergänzungen haben die Sicherheitsanalysen für den Standortvergleich mindestens die folgenden Aspekte zu umfassen:

[...]

j. Verwendung eines einheitlichen Biosphärenmodells für die Nordschweiz. Die sicherheitstechnische Bedeutung von alternativen Biosphärenszenarien ist zu berücksichtigen. Dazu sind umhüllende Szenarien von möglichen Entwicklungen insbesondere der Gebietsmorphologie und des Klimas zu betrachten.

According to the requirements of ENSI Guideline G03 and the clarifications and additions described below, the safety analyses for the site comparison must include at least the following aspects:

[...]

j. Use of a uniform biosphere model for Northern Switzerland. The safety significance of alternative biosphere scenarios shall be taken into account. To this end, enveloping scenarios of possible developments, in particular of the area morphology and climate, shall be considered.

The requirement to explore the potential evolution of the biosphere is also stated in ENSI G03:

ENSI G03, Art. 9.3.1 a:

Die Sicherheitsanalyse hat mindestens die folgenden Elemente zu umfassen:

[...]

10. Betrachtung umhüllender Szenarien von möglichen Entwicklungen insbesondere der Gebietsmorphologie und des Klimas im Rahmen der Biosphärenmodellierung.

The safety assessment has to include at least the following aspects:

[...]

10. Consideration of envelope scenarios relating to possible evolutions, in particular the area morphology and climate as part of biosphere modelling.

2.2 Endpoints of the assessment

Protection is demonstrated by assessing potential doses and risks to humans. This requires the behaviour of radionuclides released from the geosphere to be modelled in the region local to those releases. This model provides the basis for evaluating concentrations and associated potential doses to humans.

During the period under consideration (see Section 2.6 on time frames, below), regulatory criteria are defined as an individual dose constraint of 0.1 mSv a^{-1} (ENSI 2023). Over longer time frames, calculated potential doses remain of interest, but the comparison is made against average current radiation exposure of the Swiss population (ENSI 2020).

> ENSI G03, Art. 4.3.2 a:
>
> *Für keine zukünftige Entwicklung eines Tiefenlagers darf die Freisetzung von Radionukliden zu einer Individualdosis grösser als 0,1 mSv pro Jahr oder zu einer Überschreitung des Risikorichtwerts gemäss Kriterium (b) in Absatz 2.15 des IAEA Safety Standard SSR-5 führen.*
>
> Any future evolution of a deep geological repository must not lead to the release of radionuclides causing an individual dose exceeding 0.1 mSv per year, nor cause the risk value according to criterion (b) in paragraph 2.15 of IAEA Safety Standard SSR-5 to be exceeded.
>
> ENSI G03, Art. 4.3.2 c:
>
> *Nach Ende des Nachweiszeitraums dürfen die Auswirkungen an der Oberfläche nicht wesentlich höher sein als die durchschnittliche heutige Strahlenexposition der Schweizer Bevölkerung.*
>
> After the end of the assessment period, the effects on the surface must not be significantly higher than the average current radiation exposure of the Swiss population.

Reference can also be made to a risk reference value of 10^{-5} a^{-1}, enabling the likelihood of particular exposure situations to be taken into account, as required. A risk conversion factor of 0.05 Sv^{-1} is defined in ENSI Explanatory Report for Guideline G03 (ENSI 2023), which is the approximated overall fatal risk coefficient for radiological protection in ICRP (2007).

Radionuclide releases to the biosphere from geological disposal would occur over protracted periods of time, such that concentrations in the biosphere have the potential to reach an equilibrium with the rate of releases to the biosphere. Nagra's biosphere modelling (this report) delivers biosphere dose conversion factors (BDCFs) based on the calculated dose rate (Sv a^{-1}) achieved at equilibrium for continuous unit releases of radionuclides to the biosphere (Bq a^{-1}). This approach is pessimistic if radionuclide releases do not occur over a timescale that would allow equilibrium to be reached. The timescale for reaching equilibrium in the biosphere are, therefore, also of interest.

The protracted nature of potential radionuclide releases to the biosphere from geological disposal mean that lifetime doses are evaluated. In this context, and consistent with guidelines of the ICRP (2013), it is relevant to assess potential doses to adults.

2.3 Assessment philosophy and management of uncertainty

Uncertainty is unavoidable in making projections about the performance of the repository system and assessing potential consequences via biosphere modelling in the long term. This includes uncertainty due to incomplete or imprecise knowledge of processes and conditions (termed "epistemic" uncertainty). The system being modelled (in this case the biosphere) is also subject to heterogeneity and variability driven by the stochastic nature of the processes and features considered (termed "aleatory" uncertainty).

While uncertainty cannot be avoided, it can be managed by being recognised, reduced (in so far as is possible), quantified and by evaluating its effect on conclusions.

- Uncertainty about what might happen in the future (tending to be epistemic rather than aleatory) can be evaluated by assessing different scenarios and is termed scenario uncertainty.
- Uncertainty about how to model radionuclide behaviour (typically a combination of both epistemic and aleatory uncertainty) can be evaluated through different conceptualisations and modelling approaches, termed modelling uncertainty.
- Uncertainty about the parameter values and distributions to represent the system in quantitative models (tending to be aleatory rather than epistemic), termed parameter uncertainty.

Given that the aim of the assessment is to help ensure that the potential significance of any radionuclide releases to the biosphere is not underestimated (rather than aiming to make exact predictions), there is also potential to manage uncertainties by making pessimistic assumptions. In the context of the biosphere, this is reflected in ensuring that a wide range of potential exposure pathways are evaluated, with humans making maximum but reasonable usage of the local environment. To help avoid overly pessimistic assessments, pessimism about the range of potential exposure pathways is balanced by seeking to be realistic in modelling the behaviour of radionuclides in the biosphere and in adopting plausible, internally consistent assumptions about individual lifestyles.

Given the aim of providing confidence that potential radiological consequences are not underestimated and given the approach of erring on the side of pessimism in evaluating potential exposures, a deterministic approach is deemed sufficient. Consistent with the strategy of being realistic in modelling radionuclide behaviour in the biosphere, while erring on the side of pessimism in representing potential exposure pathways, best-estimate parameter values are thus adopted for characterising the biosphere and representing radionuclide migration.

Uncertainty about biosphere conditions over long timescales means adopting a stylised approach, consistent with ENSI (2023) (and with guidelines in ICRP (2013) and NEA (2012)). A deterministic reference case is developed, with uncertainties about the nature of the biosphere at the time of radionuclide releases to the near-surface being explored through a range of alternative cases considering different climate and geomorphological assumptions. Combined, these cases help to provide information on important features, events and processes (FEPs) and help to envelope the range of potential outcomes. In addition, systematic sensitivity analyses further help to identify important aspects of biosphere modelling.

ENSI Explanatory Report for Guideline G03, Art. 9.3.1 c:
[…] Bei der Modellierung von Szenarien können auch stilisierte Annahmen verwendet werden wie zum Beispiel die Biosphärenmodellierung.
[…] Conventionalised [stylised] assumptions such as biosphere modelling can also be used when modelling scenarios.

2.4 Repository system and site context

A detailed description of the current repository system (sometimes referred to as the disposal system) is provided elsewhere (Nagra 2021); nonetheless, consistent with the enhanced BIOMASS methodology (Lindborg et al. 2022), it is helpful to provide a high-level description to help place biosphere modelling in the context of the broader assessment.

In Switzerland, either two single repositories for HLW and L/ILW, respectively, or a combined repository for both waste types are envisioned. A schematic illustration of the combined repository for HLW and L/ILW is shown in Fig. 2-1. It should be noted that the landscape shown above the repository is not the modelled biosphere, as radionuclides will be transported elsewhere.

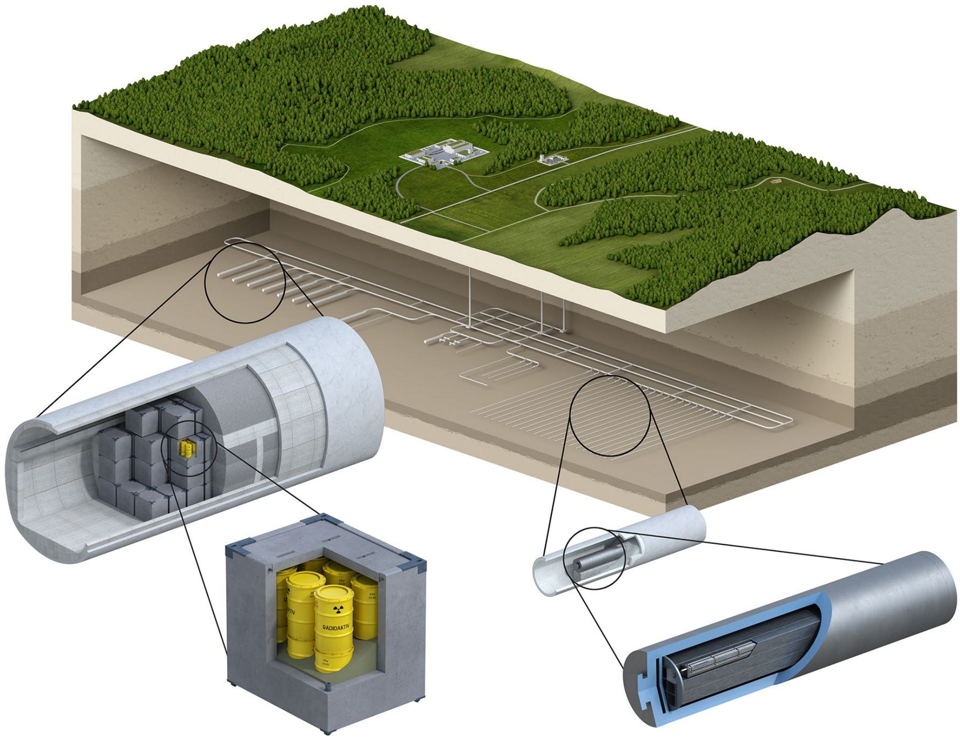

Fig. 2-1: Illustration of the combined deep geological repository in the Opalinus Clay

In the concept for HLW disposal (right), spent fuel and vitrified HLW from reprocessing are packaged in steel canisters. The canisters are placed in drifts, which are backfilled with a compacted bentonite buffer and sealed. In the concept for L/ILW disposal (left), L/ILW waste containers are placed in caverns and backfilled with cement-based mortar.

The emplacement drifts and caverns are constructed in the Opalinus Clay host rock at a depth of over 800 m, with all underground openings and access structures closed following emplacement operations and a subsequent monitoring period using a system of seals and backfill.

The geological barrier is provided by the Opalinus Clay and its confining geological units (shown in Fig. 2-2), termed the containment-providing rock zone. The Opalinus Clay is characterised by a fine and homogeneous pore structure, extremely low hydraulic permeability, a homogeneous and high clay mineral content and the associated high sorption capacity for many radionuclides.

It provides an effective and stable barrier against radionuclide transport and a suitable physical and chemical environment for the engineered barriers. Fig. 2-2 also indicates the deep aquifer layers located above and below the repository.

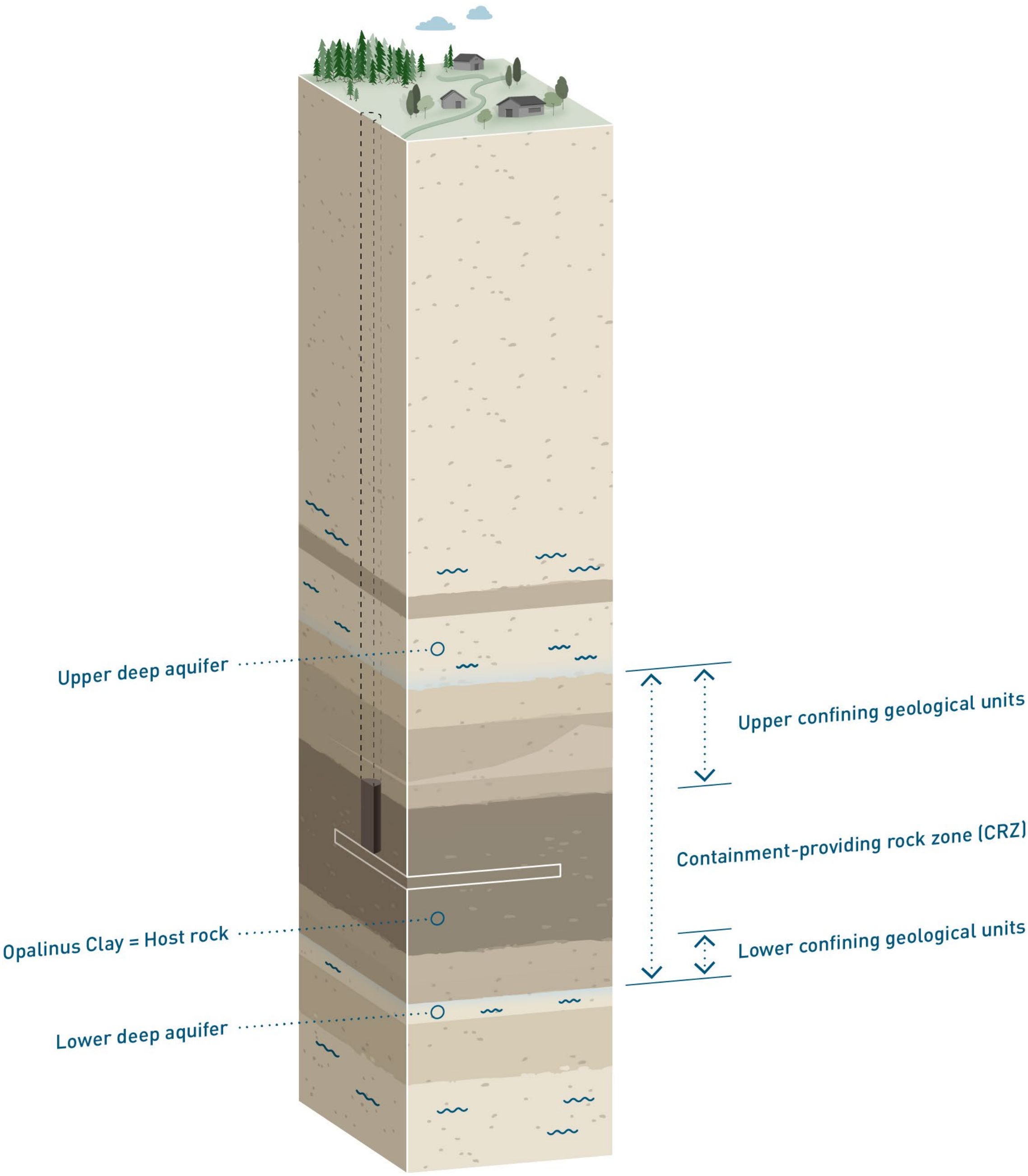

Fig. 2-2: Sketch of the location of the repository within the Opalinus Clay host rock, as well as the containment-providing rock zone (not to scale)

The containment-providing rock zone includes the Opalinus Clay and its confining units and is bounded above and below by deep aquifers.

2.5 Source term and geosphere-biosphere interface

Radionuclides are naturally present in the biosphere, and releases from the geosphere to the biosphere continuously occur through natural radioactivity. Nonetheless, where this report discusses contaminant release and behaviour in the biosphere, the focus is on the potential behaviour of radionuclides originating from the repository.

The pathway under assessment for radionuclides to reach the near-surface is potential diffusion in groundwater through the Opalinus Clay and surrounding rocks to lithostratigraphic layers that have sufficient hydraulic conductivity to provide potential groundwater pathways to the near-surface. Radiological consequence analysis focuses on representing radionuclide release and migration from the repository, along with diffusion and advection through the Opalinus Clay and adjacent rocks. Radionuclide migration along advective groundwater pathways to the near-surface is not explicitly represented; instead, assessments are undertaken on the basis that radionuclides reaching the advective layers are immediately transferred to the near-surface. This is a notable pessimism in the assessment because transport along a groundwater pathway from depth to the near-surface would cover a distance of kilometres and can be expected to take at least some thousands (to hundreds of thousands) of years (Nagra 2024d). The pessimism arises from ignoring radioactive decay and dispersion in this part of the pathway. Understanding of potential advective groundwater pathways to the near-surface can be drawn from the investigation of the palaeo-hydrogeological evolution (Nagra 2024d) and from regional-scale hydrogeological modelling (Nagra 2024e).

Given the above, the post-closure releases of radionuclides to the biosphere from, or in-grown from, disposed waste would only occur in the distant future (if at all) and would be protracted in nature, with release rates changing slowly compared to timescales for reaching equilibrium with environmental media in the biosphere (Nagra 2024g).

On the basis of screening calculations (Nagra 2024j), the following 63 radionuclides must be explicitly addressed in post-closure safety assessments:

Ac-227, Ag-108m, Al-26, Am-241, Am-242m, Am-243, C-14, Ca-41, Cf-249, Cf-251, Cl-36, Cm-242, Cm-243, Cm-244, Cm-245, Cm-246, Cm-247, Cm-248, Cs-135, Cs-137, Fe-60, Hg-194, Ho-166m, I-129, Mo-93, Nb-91, Nb-93m, Nb-94, Ni-59, Ni-63, Np-237, Pa-231, Pb-202, Pb-210, Pd-107, Po-209, Po-210, Pu-238, Pu-239, Pu-240, Pu-241, Pu-242, Ra-226, Ra-228, Se-79, Si-32, Sm-151, Sn-121m, Sn-126, Sr-90, Tc-99, Th-228, Th-229, Th-230, Th-232, Ti-44, U-232, U-233, U-234, U-235, U-236, U-238, Zr-93.

In addition to this list, Co-60, Pb-205, and Pu-244 must be included because they will in-grow from radioactive decay and have a sufficiently long half-life to merit explicit representation in radionuclide transport modelling.

2.6 Time frames

Deep geological disposal is expected to isolate the vast majority of the radioactive waste radionuclides from the surface. Over very long timescales, it may be anticipated that a small fraction of the radionuclides associated with the waste emplaced deep underground may eventually reach the near-surface. The post-closure biosphere modelling aims to evaluate the radiological consequences associated with potential releases to the biosphere in the very long term, extending to timescales of hundreds of thousands, and even millions, of years.

ENSI refer to an assessment period of up to one million years, during which assessed doses should remain below 0.1 mSv a^{-1}. Dose assessments can extend beyond that time frame, in which case they are compared with the present-day natural background dose rate in Switzerland (see Section 2.2).

ENSI G03 Art. 9.3.2 a:

Für den Sicherheitsnachweis ist ein Nachweiszeitraum von bis zu einer Million Jahre festzulegen. Die zeitliche Entwicklung des radiologischen Gefährdungspotenzials der eingelagerten Abfälle und die Prognostizierbarkeit der geologischen Langzeitentwicklung sind zu berücksichtigen.

An assessment period of up to one million years has to be specified for the safety case. The evolution of the radiological hazard potential of the emplaced waste over time and the predictability of long-term geological evolution has to be taken into account.

It must be emphasised that the post-closure biosphere modelling on timescales of tens of thousands to hundreds of thousands or even to millions of years does not aim to make exact predictions of what will happen in future. Instead, due to large and unavoidable uncertainties, the aim is to apply the best understanding that we have today to evaluate the performance over long timescales with sufficient confidence in support of the safety case.

As evidenced by palaeoclimatology, on timescales of hundreds of thousands to millions of years, the earth's climate will go through cycles of colder (glacial) and warmer (interglacial) conditions (Nagra 2024b). Factors outside this area of interest including climate, associated processes of fluvial and glacial erosion/deposition and human influences on the landscape, mean that biosphere conditions will continue to change throughout the period under consideration. Uncertainty concerning biosphere conditions at the time of any radionuclide releases in the distant future are bounded by considering reference and alternative cases that explore the implications of different climatological and morphological contexts (see also Section 2.3). It should also be noted that even during times when human surface settlement can be ruled out (e.g. due to ice coverage), the protection criterion (see Section 2.2) still has to be fulfilled on the basis of the reference biosphere.

ENSI G03 Art. 9.3.3 a:

Auch für Zeitperioden, in denen eine Besiedlung der Erdoberfläche im Einflussbereich eines geologischen Tiefenlagers ausgeschlossen werden kann, ist das Schutzkriterium von Kap. 4.3.2 Bst. a einzuhalten. Dazu ist für diese Perioden die Präsenz von Menschen in einer Referenzbiosphäre anzunehmen.

Even during times when human surface settlement within the area of influence of a deep geological repository can be ruled out, the protection criterion specified in section 4.3.2 letter a has to be fulfilled. For these periods, the presence of humans in a reference biosphere has to be assumed.

Radionuclide releases would only occur in the distant future and in the form of long-term releases in groundwater (see Section 2.5), so potential exposures would occur on timescales of human lifespans. This means that modelling has to consider the long-term behaviour of radionuclides in the biosphere, such that long-term average conditions are relevant. Shorter fluctuations, such as diurnal or seasonal changes, contribute to those long-term conditions, and thus merit consideration, but may not need to be explicitly represented.

2.7 Societal assumptions

Technological capabilities and human societies clearly have the potential to change significantly over the timescales relevant to biosphere assessment (see Section 2.6). To avoid speculation concerning technological capability and societal structure, biosphere assessments are undertaken on a stylised basis (ICRP 2013, ENSI 2023, NEA 2012) (see Section 2.3), assuming that humans will be present and will have a level of technological capability and societal structure similar to those at the present day. The capabilities and societal structure considered are considered consistent with the biosphere characteristics assessed.

Regulatory guidelines stipulate that individual doses representative of the more highly exposed groups within a population are to be assessed (ENSI 2023). In combination with the spatial scale of radionuclide dispersion in the near-surface and surface, the spatial scale for biosphere modelling can be considered to reflect an area sufficient to support a population group. In this context, a self-sufficient community is envisaged as the basis for biosphere modelling (see Section 2.1).

3 Representation of the biosphere

This chapter defines the biosphere for the post-closure safety assessment by considering its interactions with the repository system, as well as the influence of external factors; these are discussed in Section 3.1. The development of the biosphere over the very long time frame of relevance (see Section 2.6) is then described in Section 3.2, which concludes by defining a reference biosphere system, along with alternative conditions that merit consideration.

3.1 Biosphere interactions

The biosphere region considered for consequence analyses is defined as the local region primarily affected by the potential release of radionuclides in the long term. A population group can reasonably be considered to exist in this area. The analysis aims to evaluate potential doses to humans representative of the most affected population group (see also Section 2.1), so the biosphere modelling described in this report focuses on the region local to potential radionuclide releases.

In addition to being the region for which important metrics of the performance of the geological repository are defined (i.e. potential doses to humans), the biosphere also provides a boundary condition for the assessment of the geosphere and repository conditions:

- At a regional scale, the climate, topography and near-surface lithostratigraphy determine groundwater recharge and discharge rates for the regional groundwater system, thereby affecting the geosphere and repository.
- The global climate determines glacial-interglacial cycling, which will occur during the period under consideration and whereby periglacial and glacial processes will influence the deeper system.
- The landscape will continue to evolve over the period under consideration by processes such as erosion and sedimentation; this evolving landscape may affect the regional pattern of groundwater recharge and discharge affecting the deeper system.

Consideration of the biosphere for consequence analysis, therefore, must be consistent with how it is represented in other components of the overall safety assessment. This is achieved by coordination across the different components of the assessment and aided by drawing upon the same supporting research. Notably, further information about the future climate, landscape and hydrogeological evolution can be found in the geosynthesis report (Nagra 2024d). Moreover, a dedicated report (Nagra 2024b) addresses the climate evolution over long timescales. Similarly, there are dedicated reports concerning the modelling of the regional groundwater system (Nagra 2024e) and the erosion over long timescales (Nagra 2024c). Over extremely long timescales, uplift and erosion may reduce the extent of the geological barrier. A separate report evaluates radiological consequences in the hypothetical case of an excavation via glacial or non-glacial processes in the distant future (Nagra 2024h).

There are four key interrelated external factors that will determine the nature of the surface and near-surface environment in Northern Switzerland in the distant future, when radionuclide releases from a geological repository to the biosphere via groundwater might occur:

- the global and regional climates;
- geodynamics, erosion and sedimentation;
- regional hydrogeology;
- surface hydrology; and
- human behaviour.

These are individually discussed below.

Over the past one million years (Ma), the earth's climate has been subject to cycles of glacial and interglacial conditions, with an overall periodicity of about one hundred thousand years (100 ka) during the last 800 ka, and with interglacial conditions typically lasting some several thousands of years (Nagra 2024b). The last glacial maximum occurred around 24 ka before present (BP). Anthropogenic emissions of greenhouse gases mean that the earth's climate is expected to experience a prolonged period of interglacial conditions. The next glacial inception is considered very unlikely for another 50 ka after present (AP), and is not expected to reach full glacial conditions for 200 ka AP or even longer, depending on greenhouse gas emission and mitigation scenarios (Nagra 2024b). Glacial conditions are accompanied by ice sheet development over the Alps and Northern Switzerland, with the extent dependent upon the intensity of glacial conditions.

The current landscape of Northern Switzerland, with valleys and hillsides, has been shaped by endogenic and exogenic processes, including tectonic uplift, erosion, and sedimentation under glacial and non-glacial conditions. Hence there is an indirect link to climate conditions. Over the period under consideration, erosion and sedimentation patterns in Northern Switzerland are expected to be similar to those that have occurred over the last one million years. Present-day topography and near-surface lithostratigraphy in Northern Switzerland therefore provide an analogue for conditions in the future when radionuclide releases into near-surface groundwater could occur.

Palaeohydrogeological investigations and regional hydrogeological modelling have been undertaken to analyse groundwater conditions within and around the host rock, and to relate potential groundwater pathways from great depths to the near-surface (Nagra 2024d, Nagra 2024e). Regional hydrogeological modelling supports previous observations (Haldimann & Schatzmann 2014) and analyses (Nagra 2014) by indicating that deep groundwater will likely discharge to topographic lows. In the context of Northern Switzerland, this means that deep groundwater will mainly discharge to valley bottoms. Discharge of deep groundwater is also expected to occur towards larger river valleys in Northern Switzerland, such as the Rhine valley. This is supported by previous (Gmünder et al. 2014) and more recent (Nagra 2024e) hydrogeological modelling, which shows potential pathways discharging to larger valleys along the Malm, Hauptrogenstein, Keuper and Muschelkalk aquifers. Discharge of deep groundwater to the near-surface in the context of Northern Switzerland is illustrated in Fig. 3-1.

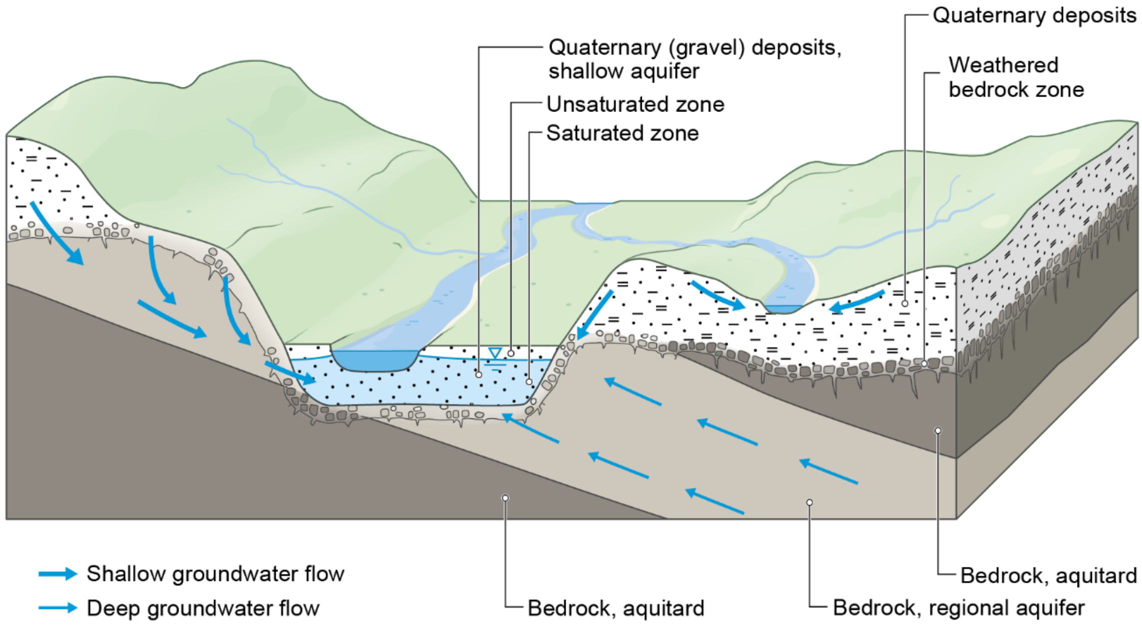

Fig. 3-1: Conceptual model of deep groundwater discharge to a valley in the context of Northern Switzerland

Not to scale.

In addition to climate, (hydro)geology and surface hydrology, human behaviour will shape the character of the biosphere of Northern Switzerland, as it currently does. During periods of continental climate or in warmer conditions, agriculture and arboriculture are feasible, with associated impacts on the landscape through patterns of fields and forestry. Actions to facilitate agriculture and forestry can also be expected, including the use of field drains to lower shallow groundwater levels. Other forms of surface water management can be anticipated, including channelling rivers and, potentially, installing dams; post-glacial lakes will form a notable feature of the landscape in Northern Switzerland regardless.

Radiological consequence analysis focuses on situations that reasonably maximise potential exposure rates, which typically equate to agricultural use of the landscape, including extended irrigation from local water sources, where the range of potential exposure pathways is greatest. The landscape will also include roads, housing and other infrastructure to facilitate occupation and use by the local population. These are expected to have relatively limited impact on determining potential exposures in an agricultural setting and are accounted for by drawing on understanding of present-day systems in defining/parametrising the biosphere, where these features exist.

3.2 Biosphere development

As a result of the processes discussed in Section 3.1, the surface environment will change on timescales of tens to hundreds of thousands of years through processes driven by climate, erosion, sedimentation, hydrology/hydrogeology and human behaviour. In assessing the potential significance of radionuclide releases to the biosphere over long timescales, it is necessary to consider how such changes should be taken into account.

Radiological assessment requires modelling of the potential behaviour of contaminants in the biosphere over the period when radionuclide releases into the biosphere can occur. Although the biosphere will change over the long timescales relevant to the consequence analysis, these changes can be expected to be slow (i) relative to the timescale of processes that determine the fate of contaminants in the biosphere, and (ii) relative to the timescale of potential exposure (i.e. human lifespans).

As long as biosphere conditions consider the use of the environment where radionuclides can be discharged, it is not necessary to explicitly model the gradual long-term changes and transitions of the biosphere. This has, for example, been demonstrated in the context of deep geological disposal in SKB (2019), including glacial-interglacial cycling.

Nagra's approach to considering environmental change in the context of biosphere modelling is, therefore, summarised as follows.

- Biosphere conditions in the vicinity of potential locations of radionuclide releases into near-surface groundwater will change over timescales relevant to the consequence analysis.
- There is no need to explicitly model biosphere changes that occur before radionuclides can reasonably be expected to be released to the biosphere. Only those conditions must be represented that could be present when those releases can be expected to occur.
- There is no need to explicitly model the gradual changes that will occur after radionuclides can potentially begin to be released into the biosphere, as long as conditions that result in reasonable maximum exposures are assessed.
- The range of potentially relevant biosphere systems when radionuclide releases into the near-surface groundwater can occur have to be considered. This is achieved by identifying reference conditions and alternative cases to suitably envelope the range of future conditions where exposures can occur.

Climate conditions

Present-day biosphere conditions in Northern Switzerland provide a natural point of comparison and have previously been used as a basis for defining the reference biosphere for consequence analysis (Klos et al. 1996, Nagra 2002a, Brennwald & van Dorp 2008, Nagra 2010, Nagra 2014). Interglacial conditions, such as those that exist today, are sufficient to support a wide range of types of agriculture in the valleys of Northern Switzerland, which allow for the broadest range of potential exposure pathways to be included.

Although global warming will result in increased temperatures relative to the present day, the extent of the associated effects on climate conditions in Northern Switzerland is uncertain, as is the duration of any such conditions. Humanity will transition away from fossil fuel sources within a timescale of hundreds of years, either by choice or necessity, e.g. as carbon sources become increasingly difficult to exploit. Although the effect of anthropogenic emissions will persist, various mechanisms will remove excess carbon dioxide from the atmosphere (IAEA 2020), so that the magnitude of perturbation from natural climate variation will decline with time (Talento & Ganopolski 2021). However, this can take up to 500 ka or more, depending on the considered emission scenario. Radionuclide releases from a deep geological repository to the biosphere will likely not occur before any peak impact from anthropogenic mission on greenhouse gases. Therefore, the present-day climate is used as a basis for reference biosphere conditions. Nonetheless, a calculation case based on warm climate conditions remains of interest as an alternative, which is consistent with previous assessments (e.g. Brennwald & van Dorp (2008), Nagra (2010), Nagra (2014)).

Both palaeoclimatology and projections of global climate extending to one million years into the future demonstrate that the earth's climate will be significantly colder than it presently is for much of the period under consideration (Nagra 2024b, Talento & Ganopolski 2021). Under full glacial conditions, humans will not likely be present in the Northern Switzerland (e.g. due to ice sheet coverage), and the presence of an ice sheet would limit groundwater recharge and, therefore, significant flow rates. However, periods can be expected when the climate is colder than at present, but during which human occupancy may still be feasible. This might occur, for example, as the climate cools towards full glacial conditions, the climate moves from glacial to interglacial conditions, and during periods when the climate may cool, but then recover to interglacial conditions without having achieved full glacial inception. Previous Nagra assessments have included consideration of a cold climate biosphere (Nagra 2010, Nagra 2014), which is retained here as an alternative.

During periods when human habitation can be ruled out (e.g. during full glacial conditions), consequence analyses can still be undertaken, for example, using reference biosphere conditions, to provide reassurance that potential radionuclide releases remain within acceptable bounds. This approach is consistent with ENSI guidelines (see Section 2.6).

That climate will evolve on long timescales is certain. Those changes will typically be relatively gradual, such that the climate will proceed through sequences of different climate states. In principle, it would be feasible to develop a range of biosphere models reflecting a broad range of climate permutations. However, warm and cold climate conditions provide bounding cases, which, in combination with the reference biosphere case based on the present-day climate, are considered to provide a suitable envelope of conditions for the purpose of the assessment.

Morphological situations

Valleys in Northern Switzerland tend to have glaciofluvial deposits over bedrock, providing relatively flat valley floors. The valleys tend to have rivers and lakes. Previous Nagra assessments have focused on reference biosphere conditions represented by a valley with a river, on the basis that this environment allows for agricultural usage and a broad range of potential exposure pathways (Klos et al. 1996, Nagra 2002a, Brennwald & van Dorp 2008, Nagra 2010, Nagra 2014). Significant post-glacial lakes are present in the landscape of Northern Switzerland, e.g. on over-deepenings associated with deep glacial erosion. However, the low permeability of sediments beneath the lakes constrains interaction with deeper groundwater, and the typical size of the lakes means there is significant dilution within the large volumes of water. For these reasons, radio-nuclide releases to a river system provide a more pessimistic point of reference. Therefore, re-leases to lakes do not have to be explicitly represented (Nagra 2002a).

Optimal agricultural conditions will be achieved with the groundwater table at a depth of some metres from the surface, thereby avoiding water-logged soils and facilitating a broad range of crop types and livestock. There are areas within Northern Switzerland where the water table would naturally be closer to the soil surface; these areas might have been natural wetlands but have typically been managed by humans through use of field drains/ditches to lower the water table, thereby improving agricultural productivity (see Stuber & Bürgi (2021)). These areas re-present a relatively small proportion of valley bottoms in the region of interest (e.g. Gimmi et al. (2011)). Nonetheless, potential for groundwater to be closer to the soil surface means that there is merit in including an alternative case for drained land agriculture.

Within the present-day landscape in Northern Switzerland, there are small regions where lime-stone bedrock has a greater than typical influence. The area of Randen close to Schaffhausen or the Tabular Jura to the west of the lower Aare valley provide examples of regions characterised by outcropping Mesozoic units, including connection to units acting as deeper aquifers. In these areas, agriculture is also generally concentrated in valley bottoms over unconsolidated porous materials. The karstic nature of the subsurface geology in these areas means that groundwater drains relatively freely, resulting in relatively thin shallow aquifers. The free-draining nature of the hillsides and valley bottoms means that there is less surface runoff and relatively little surface water. The general structure of these systems is, therefore, similar to the more typical valley systems in Northern Switzerland, with distinction primarily by size and water flow rates. These environments are encompassed in reviews that support characterisation of the biosphere, including Haldimann & Schatzmann (2014), and are therefore encompassed within parameter ranges used in sensitivity calculations (see Section 6.3.1).

Cases to be considered

In summary, biosphere modelling focuses on a reference case based on a present-day climate with groundwater from deep aquifers discharging to a porous shallow aquifer in a valley bottom, with the area local to the release being used for agriculture. Alternative cases explore potential consequence of releases to warmer-drier and cold climate conditions. Another alternative case explores potential consequences of discharges to regions where groundwater is naturally closer to the surface and the landscape has been drained for agriculture. The cases aim to bound potential dose consequences. Narrative descriptions of the reference biosphere and alternative cases are provided in the subsections below. The selected cases provide a suitable envelope of climatic and morphological conditions.

3.2.1 Narrative description of the reference biosphere

The reference biosphere case draws on understanding that can be gained from the region at the present-day, effectively treating today's environment as an analogue for situations that could potentially occur in the distant future, when radionuclide releases in groundwater might occur. The main point of interest is on a valley system with the potential to receive groundwater from depth (referred to as "deep groundwater" in Fig. 3-1) that can include radionuclides originating from the repository. The overall bounds of the reference biosphere are illustrated in Fig. 3-2. The principal characteristics of the reference biosphere system are described below, using a categorisation that is consistent with the enhanced BIOMASS methodology (Lindborg et al. 2022).

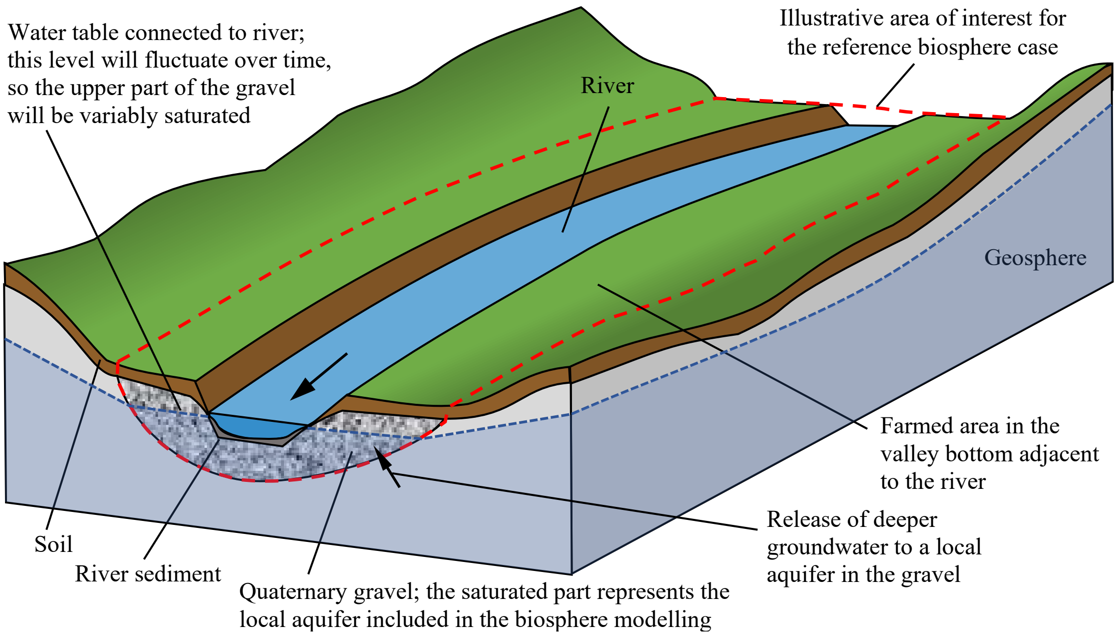

Fig. 3-2: Illustration of the extent and main physical components of the reference biosphere case

Not to scale.

Geographical location and extent: Assessment focuses on regions in Northern Switzerland where deep groundwater has the potential to carry radionuclides from the repository depth and to discharge to the near-surface. Regional-scale hydrogeological modelling demonstrates that groundwater flows in a general northern direction from depth. Accordingly, areas of interest lie to the north of the siting regions (Nagra 2024e). Groundwater pathways from depth would tend to discharge towards larger river valleys (Nagra 2024e).

The areal extent of the biosphere that must be modelled for dose assessments is defined by consideration of (i) the spatial extent of the local near-surface aquifer into which the deeper groundwater discharges, and (ii) the spatial extent required to support a community that has a self-sufficient lifestyle. Combined, these result in a spatial scale of a few square kilometres. Biosphere characteristics within this region are taken to be relatively homogeneous.

Focus on evaluating potential doses in an area local to the point of deep groundwater release, along with consideration of human habits that lead to relatively high potential exposures, mean that there is no need to evaluate potential doses downstream of the discharge area. This is due to the fact that additional mixing and dispersion with clean groundwater, surface water and sediments mean that dose consequences down-gradient would be lower.

Climate and atmosphere: The present-day climate in the valleys in Northern Switzerland is borderline between oceanic and continental temperate (Cfb and Dfb according to the Köppen-Geiger climate classification, Beck et al. (2018)), with warm summers and reasonably cold winters, including some periods of snowfall and snow coverage, followed by thaw.

As noted in Section 2.6, if radionuclides are released into the biosphere after repository closure, this would only occur in the distant future and on timescales that are long in comparison to human lifetimes. The endpoint of the assessment is, therefore, average lifetime exposures (see Section 2.2), which means that biosphere modelling has to consider long-term average conditions. Short-term changes, such as diurnal and seasonal changes, are important in establishing the longer-term average conditions, but do not have to be explicitly represented in the modelling.

Topography: The topography for the reference biosphere case is defined by the valley section. The focus is on the valley floor where soils and sediments interact with the subsurface lithology into which radionuclides originating from the repository can discharge. The valley floor is also the area with relatively few constraints over the range of agricultural practices and associated potential exposure pathways.

Valley sides will contribute to the context of the valley floor and will provide uncontaminated groundwater and sediments to the valley floor area. The slope and extent of valley sides will affect the context for the reference biosphere case. However, they do not overlie the local near-surface aquifer and are not exposed to potential contamination.

Near-surface lithology: The valley floor comprises unconsolidated Quaternary sediments of glaciofluvial origin. These are porous and in contact with the river (see Fig. 3-2). The groundwater table sits within the unconsolidated Quaternary sediments, so there is a saturated zone (forming a local shallow aquifer) overlain by an unsaturated zone. The groundwater level will fluctuate over a typical year, so the upper part of the unconsolidated Quaternary sediments is termed the "variably saturated zone".

The topsoil is considered suitable for supporting a broad range of agricultural land use and is, therefore, assumed to be well drained. The extent of the topsoil is defined by the typical rooting and ploughing depth. The topsoil comprises weathered underground Quaternary sediments (representing the substrate), sediment deposited following hillside erosion, dead organic matter from plant roots, soil biota, material ploughed back into the soil and material used for soil conditioning (e.g. manure). The overall content of dead organic matter is relatively low, such that the soil remains predominantly mineral. The soil is slightly acidic and consists of relatively fine-grained sandy minerals (see also discussion in Metcalfe et al. (2023)).

The layer between the topsoil and the variably saturated zone of the unconsolidated Quaternary material is referred to as the deep soil. This is an unsaturated intermediate zone where the substrate is weathered and there is greater biological and geochemical influence from the topsoil compared with the variably saturated zone, but where there is less dead organic matter compared to the topsoil. The weathered nature of the material means that it is relatively fine-grained.

The flow rate within the river will be higher during the spring as a result of snow melt at higher altitudes. River bed sediments in Northern Switzerland tend to be coarse in nature because finer sediments are carried away during periods of high flow.

Further details and supporting reviews concerning the geochemical properties of the near-surface materials are provided in support of the sorption review (Metcalfe et al. 2023).

Subsurface and surface water bodies: The saturated zone within the unconsolidated Quaternary deposits has sufficient hydraulic conductivity and storage to be amenable for exploitation by humans and is, therefore, considered as an aquifer. Groundwater transport in the local aquifer is dominated by flow along the valley, with inflow from deeper groundwater providing a relatively small additional contribution.

The water table is considered to be connected with the river and has the potential to discharge groundwater from the local aquifer to the river (illustrated in Fig. 3-2). This allows potentially contaminated groundwater to discharge to surface water. The alternative situation, where the river is disconnected from the local aquifer, is also feasible. This would result in the river losing water to the local aquifer, thereby additionally diluting groundwater flow through the aquifer. Radionuclides would have no direct pathway to reach the surface water.

As noted above, groundwater from repository depth will discharge to larger river valleys in Northern Switzerland, so the characteristics of the river for the reference biosphere case draw on understanding of the Rhine.

Terrestrial and aquatic biota: The present-day landscape of Northern Switzerland has been extensively managed by humans; this, and the focus on agricultural land use, means that terrestrial biota are dominated by the agricultural context. Aside from agricultural crops and livestock, other terrestrial biota will be present, including soil biota, wildlife along hedgerows, and small semi-natural areas (e.g. small-scale woodlands and wetlands). The assessment focuses on evaluating potential doses to humans as a measure of post-closure safety, such that biota dose assessment is not required (see Section 2.2); therefore, livestock and crops (including pasture) and other biota are taken into account insofar as they may affect the distribution of radionuclides in the biosphere (e.g. via bioturbation).

A range of aquatic and marginal plants and animals will be present within and alongside the river. Focus on evaluating potential doses to humans means that fish are of particular interest, as the river is large enough to provide fish for consumption.

Human communities: A self-sufficient community is envisaged (see Section 2.7), which implies a focus on a rural, agricultural lifestyle. A population density of around 100 humans per square kilometre is estimated, consistent with previous Nagra assessments. With a spatial extent of a few square kilometres (discussed under geographical location and extent above and consistent with previous assessments), corresponding to a rural agricultural community of a few hundred humans. This number is small in terms of "population" scales referenced in international (ICRP 2013) guidelines. Nonetheless, this scale of population is consistent with the objective of erring on the side of pessimism in evaluating potential dose consequences (see Section 2.3).

The community is assumed to make reasonable maximum use of local food and drinking water and to maximise time spent in the area of interest. This means that the biosphere area is used for a range of crops (cereals, fruit and vegetables) as well as for raising livestock.

Given that the source term to the biosphere is the discharge of groundwater potentially carrying radionuclides from the repository into the shallow aquifer, the community is thus assumed to make use of this shallow aquifer for a range of purposes, including drinking water for humans and livestock and for irrigation. This includes irrigation of pasture, which is a pessimistic assumption, but is consistent with previous Nagra reviews and assessments (see Nagra (2014) and, in particular, discussion in Appendix A therein).

3.2.2 Narrative descriptions of alternative biospheres

Uncertainty about conditions in the distant future, when radionuclides originating from the repository can reach the biosphere in groundwater, is addressed by considering a broad range of potential exposure pathways, erring on the side of pessimism in defining exposure rates, and through cases that explore the dose implications of alternative climate and morphological contexts. Warmer-drier and cold climate cases are identified as bounding alternative climates for biosphere modelling. In addition, release to a valley where groundwater would naturally be closer to the soil surface is proposed to encompass an alternative morphology (termed the "drained farmland" case) that is of interest from a dose assessment perspective.

A narrative description of each of these alternative cases is provided below, with a focus on describing differences compared to the reference biosphere case. In all cases, the source term remains radionuclides discharging in groundwater to a shallow aquifer in a valley bottom context.

<u>Warmer-drier climate case</u>: This case differs from the reference through a warmer and drier climate, consistent with more Mediterranean-type conditions (Csa and Csb according to the Köppen-Geiger climate classification, Beck et al. (2018)). Warmer temperatures and lower rainfall mean that there are lower water flows through the shallow aquifer and river (and thus a lower degree of dilution) and a greater drive for irrigation from the shallow aquifer (an important pathway given that the groundwater source term is directly linked to the shallow aquifer). Otherwise, the range of processes and potential exposure pathways remains identical to the reference biosphere case.

<u>Cold climate case</u>: This is a bounding case and recognises that periods must be anticipated during the period under consideration when the climate will be significantly colder than it is at present. Conditions akin to those in Northern Scandinavia and in Canada, classified as Dfc according to the Köppen-Geiger climate classification (Beck et al. 2018), will remain amenable to human habitation and continue to produce and sell a reasonable amount of local foods. This implies average temperatures below 0 °C during the coldest months, and only one to three months with average temperatures above 10 °C, with no particular dry season. The climate will be subarctic/periglacial and the natural landscape will be that of a tundra.

Consideration of climate analogue situations in BIOCLIM (2004) shows that there can be notable differences in the extent of precipitation in different cold climate contexts, with total annual precipitation ranging from around 300 to 1000 mm. Much of the precipitation will fall as snow, and there would be extensive snowpack development and freezing of the river during winter months. Spring thaw would be a particularly active hydrogeological period and result in high flow rates for surface water and groundwater.

The geographical context for the cold climate case remains identical to that for the reference biosphere case, with potential radionuclides flowing from the deep geological repository through groundwater and being discharged to the near surface. For the cold climate case, the region will remain characterised by valleys with discharge to topographic lows at the valley bottom (i.e. as in the reference biosphere case). For the purpose of the cold climate case, the valley floor is assumed to include glaciofluvial sediments, as in the reference biosphere case. The glaciofluvial sediments form a porous aquifer into which the potentially contaminated deep groundwater is released.

A layer of permafrost is assumed to be present between the aquifer and surface soils, such that there is no groundwater exchange between these layers. In the absence of irrigation with groundwater, capillary rise processes and diffusion through the permafrost layer, the only mechanism for radionuclides from the local aquifer to reach the topsoil will be gradual weathering and mass erosion over long periods of time.

The permafrost is taken to be discontinuous across the valley as whole, with connectivity maintained between the local aquifer and a river via a talik. Groundwater can, therefore, discharge from the aquifer to the river via bed sediments.

The topsoil is seasonally frozen and, together with the top of the deep soil, forms an active layer above the permafrost. Tundra soils over permafrost (cryosols) are relatively thin and poor in nutrients. However, the cold temperatures mean that mineralisation of organic matter can be very slow, and the soils can be relatively high in organic carbon. The "deep soil" is also thin, relative to the reference biosphere case, and will be seasonally frozen and variably saturated.

Under cold climate conditions, soils are not suited for large-scale modern intensive agriculture. However, herding of livestock, such as reindeer, is feasible, although large resource areas would be needed, and there is also potential to collect wild foods. Consideration of the diet of the Sámi people in Northern Scandinavia demonstrates that herding communities living in cold climates can have a relatively high intake rate of meat (Brustad et al. 2008).

Small-scale agriculture may be feasible during the summer months, including potential for greenhouses/polytunnels providing protection from harsh conditions and extending the growing season. There is potential for some irrigation in the summer (e.g. in greenhouses/polytunnels), with this reasonably being taken from the local surface water, which will have plentiful supply. The range of potential crops is considered to be limited to green vegetables and root vegetables, with other crops being supplied from elsewhere.

For communities living in permafrost-affected regions drinking water is typically taken from surface water (see Lemieux et al. (2020)), because of its abundance and ease of access. Given the short growing season, the local horticulture is considered to have a limited potential for production and cultivation of some crops (e.g. cereals) may not be feasible under these conditions.

<u>Drained farmland case</u>: The case is motivated by the observation that there are areas in the valleys of Northern Switzerland into which deep groundwater can discharge (Stuber & Bürgi 2021). In these areas, the water table would naturally be closer to the soil surface compared to the reference situation. Over time, the groundwater level in many of these wetland areas has been lowered through the use of drainage ditches and field drains to allow the land to be used for agriculture. Even though the areas represent a relatively small proportion of the overall landscape, this is of interest because groundwater is closer to the surface.

The structure of the biosphere is effectively identical to for the reference case, with unconsolidated Quaternary deposits overlain by soils. The water table would naturally be close to the soil surface for the drained farmland case, although it is assumed to have been lowered through use of ditches and field drains to improve conditions for agriculture. As such, the water table is situated within the deep soil. Although unsaturated, the topsoil has a higher organic matter content compared to the reference biosphere case because of its origin as a wetland soil.

The deep soil drains directly into the surface water via the field drains and ditches. However, these ditches are too small to provide any fish for human consumption. There is remaining potential for some groundwater discharge from the upper part of the unconsolidated Quaternary sediments to the river. During wetter periods, the soil can be flooded by the river, which means that river sediments can be transferred to the land.

Even though the water table is lowered, the generally wetter conditions, with groundwater closer to the soil surface and flooding, mean that the area is less suited for some types of agriculture. In this case, it is assumed that cereals and fruit are grown elsewhere, while the land can still be used for growing green vegetables, root vegetables, and pasture. Wetter conditions mean that there is no need for irrigation of crops or pasture. However, they can be impacted by flooding.

Drinking water for livestock is obtained from surface water. Groundwater continues to be used as a source of drinking water for humans, because it will be cleaner than the surface water and is readily accessible given the shallow water table.

4 Biosphere assessment modelling

The biosphere, as conceived for long-term, post-closure safety analyses, is defined in Chapter 3. To represent each of the biosphere systems, the process for developing dose assessment models (Lindborg et al. 2022) involves (i) developing a conceptual model of the FEPs that have to be considered to understand radionuclide transport and exposure (Section 4.1) as a basis for (ii) developing a mathematical model (Section 4.2). Assumptions, uncertainties and the calculation cases are then summarised in Section 4.3.

Nagra's approach to representing the biosphere has been consistent throughout the SGT process. The underlying conceptual model, the mathematical model and the supporting dataset were originally established in the TAME code (Klos et al. 1996) and have subsequently been refined and maintained throughout Nagra's assessment cycles.

4.1 Conceptual model development

The conceptual model of radionuclide transport and exposure for the reference biosphere case is described in Section 4.1.1, and those for the alternative cases in Section 4.1.2. The calculation cases, key assumptions, pessimisms and management of uncertainty are summarised and discussed in Section 4.3.

4.1.1 Reference biosphere

Based on the principal characteristics described in Section 3.2.1, including the spatial extent, the following principal components of the reference biosphere case that require representation in modelling radionuclide transport and exposure can be identified:

- Unconsolidated Quaternary sediments in the valley that receive radionuclides from the depth via groundwater; these can be distinguished into:
  - saturated sediments, forming a local aquifer, and
  - a variably saturated/unsaturated zone above the local aquifer;
- Lower soil horizons between the topsoil and variably saturated unconsolidated Quaternary sediments;
- Topsoil, defined by rooting depth, ploughing and bioturbation;
- Surface water (river), which can be distinguished into:
  - the water itself, including suspended sediment, and
  - the river bed sediment in contact with the unconsolidated Quaternary sediments;
- Atmosphere above the soil and river;
- Plants growing on the topsoil with the main focus on agricultural crops for the purpose of exposure assessment;
- Terrestrial animals with the main focus on livestock for the purpose of exposure assessment;
- Aquatic animals with the main focus on fish for the purpose of exposure assessment;
- Humans, specifically, the locally exposed population.

These principal components form the features that must be included in the reference biosphere model. Radionuclides can be released into the system through groundwater discharging from depth. Uncontaminated water and solids can enter the valley section of interest from an up-gradient. However, material (including water and sediments) can also be lost from the section of interest to elsewhere.

The overall structure of the reference biosphere, and the events and processes that result in radionuclide migration and potential exposure can be conceptualised in terms of an interaction matrix, where the features are represented as lead diagonal elements, and the events and processes as off-diagonal elements (see e.g. Lindborg et al. (2022)). Interaction matrices are helpful tools in translating narrative descriptions into conceptual models because they provide a framework for explicit consideration of potential events and processes operating between all of the features that have to be represented. An interaction matrix for the reference biosphere case is provided in Fig. 4-1 (the general configuration is also illustrated in Fig. 4-2 and Fig. 4-3).

The biosphere will also include uncultivated plants, algae and fungi. However, potential exposures are considered to be dominated by agricultural pathways, such that "crops" form a principal component, as illustrated in Fig. 4-1. The extent to which other plants, algae and fungi affect radionuclide behaviour in the biosphere can be taken into consideration in parameterising other processes, e.g. degradation of organic matter in soil in relation to modelling C-14 in the biosphere (Guillemot et al. 2024).

Similarly, animals other than livestock will be present in the biosphere. However, as with plants, potential exposures are considered to be dominated by agricultural pathways, such that terrestrial "animals" in Fig. 4-1 can be considered to reflect livestock. The extent to which other animals (and microbes) affect radionuclide behaviour in the biosphere can be taken into consideration in parameterising other processes, e.g. bioturbation.

Timescales for some biosphere processes are fast relative to timescales for radionuclide releases to the biosphere and other processes that determine the long-term average concentrations in components including the aquifer, surface soils and bed sediments. These fast processes include releases from soils to the atmosphere, soil-to-plant uptake, transfers from feed to animal produce and uptake of radionuclides from surface water by fish. Where principal components of the biosphere are only affected by these relatively fast processes, they can be considered to be in equilibrium with their surrounding environment and are highlighted in Fig. 4-1.

In developing the conceptual model, assumptions are needed to identify FEPs that require explicit representation and to identify some processes that are of limited significance in assessing potential radiological consequences. These "screening" considerations are discussed in Tab. 4-1.

Some processes operate at a scale that lies within the principal components illustrated in Fig. 4-1 and are, therefore, not explicitly listed. Important examples are identified as follows:

- Radioactive decay and in-growth occurs in all principal components.
- Sorption/desorption and associated processes (precipitation, complexation, dissolution) occur between solid and liquid phases within the principal components, especially within soils and sediments.

Conceptualisation of the reference biosphere case is discussed further in the subsections below and distinguished into FEPs associated with radionuclide transport in the biosphere (Section 4.1.1.1) and evaluation of potential exposures (Section 4.1.1.2). Screening of biosphere FEPs is also discussed in Nagra (2024j). The biosphere modelling described in this report has been reviewed against that screening to ensure consistency and to help build confidence that the important FEPs are appropriately represented.

	1	2	3	4	5	6	7	8	9	10	11	12
1	**Deep groundwater**	Release					Release					
2	Recharge Diffusion	**Local aquifer**	Capillary rise Diffusion Weathering/ erosion Suspended sed.		Irrigation Suspended sed.	Advection Suspended sed. Diffusion	Advection Suspended sed. Diffusion	Degassing	Irrigation Suspended sed.	Ingestion Suspended sed.	Ingestion Suspended sed. Bathing	Advection Suspended sed. Extraction Diffusion
3		Recharge Diffusion Suspended sed.	**Variably saturated zone**	Capillary rise Weathering/ erosion Diffusion Suspended sed.		Advection Suspended sed. Diffusion	Interflow Suspended sed. Erosion					
4			Percolation Diffusion Suspended sediment	**Deep soil**	Capillary rise Bioturbation Weathering/erosion Diffusion		Interflow Suspended sed. Erosion					
5				Percolation Bioturbation Diffusion Suspended sed.	**Topsoil**		Erosion Interflow Suspended sed.	Degassing Evaporation Resuspension (dust)	Root uptake External contamination	Ingestion	External irradiation Inadvertent ingestion	
6		Recharge	Percolation Suspended sed. Diffusion		Deposition (from flooding)	**River bed sediments**	Advection Resuspension Diffusion				Ingestion (inadvertant)	
7	Recharge Diffusion				Irrigation Flooding (water and sed.)	Sedimentation Advection (recharge) Diffusion	**Surface water**	Degassing Gas evolution Spray (irrigation) Evaporation	Irrigation	Ingestion Suspended sed. Uptake (fish)	Ingestion Bathing	Suspended sed. Advection Extraction
8					Precipitation and infiltration Gas exchange Deposition		Precipitation (and runoff) Deposition	***<u>Atmosphere</u>***	Precipitation Photosynthesis Deposition	Inhalation (gas and dust)	Inhalation (gas and dust)	Air flow
9				Root exudation Root respiration Senescence	Respiration Root exudation Root respiration Senescence			Transpiration Respiration	***<u>Crops</u>***	Ingestion	Ingestion	Cropping
10					Manure Excretion		Excretion	Exhalation Eructation		***<u>Animals</u> (farm animals and fish)***	Ingestion	Produce
11								Exhalation			***<u>Humans</u>***	Excretion
12		In-flow (water and suspended sed.)			Deposition		In-flow (water and suspended sed.)	Exchange				**Elsewhere**

Fig. 4-1: Interaction matrix showing process of radionuclide migration and potential exposure for the reference biosphere case

Features are represented as lead-diagonal elements (see also notes in Tab. 4-1). Events and processes that result in radionuclide migration and/or potential exposure are included as off-diagonal elements. Interactions are illustrated in a clockwise direction (illustrated with blue arrows for interactions between the deep groundwater and local aquifer).

Configuration of the biosphere system is illustrated in Fig. 4-2 and Fig. 4-3. Features that can typically be represented through equilibrium assumptions are highlighted in lead-diagonal elements in ***<u>italic and underlined</u>***. Aside from the deep groundwater (which is the source term), the remaining features need to be explicitly represented in dynamic modelling of radionuclide transport. Events/processes that are recognised but screened out from having to be explicitly considered in the transport and exposure modelling are included in grey font and discussed in Tab. 4-1.

Commentary is provided in Tab. 4-1. The numbered rows/columns allow for clear referencing.

Tab. 4-1: Commentary associated with the conceptualisation of the reference biosphere case illustrated in Fig. 4-1

"Position" refers to the row and column number in Fig. 4-1. Lead-diagonal elements (features) are referred to as LDEs; off-diagonal elements (events/processes) are referred to as ODEs.

Position	Comment
1,7	Deep groundwater can potentially be directly released to surface water. However, the reference biosphere case is based on release to a shallow local aquifer; comparison with direct release to surface water is included as a sensitivity calculation in Section 6.3.1.
2,7	There is potential for a direct connection between the shallow local aquifer and the surface water. However, the reference biosphere case assumes discharge via river bed sediments, which allows for a greater degree of interaction.
7,1	A potential for recharge from the local aquifer to depth is recognised. However, it would only serve to remove radionuclides from the biosphere, which would reduce potential dose consequences, and is therefore conservatively ignored.
4,4; 5,5	Deep soil and topsoil include organisms contained within them (e.g. microbes and soil fauna). These will be involved in processes that affect radionuclide distribution, e.g. through bioturbation in 4,5 and 5,4.
2,2; 3,3; 4,4; 5,5; 6,6	Unconsolidated Quaternary sediments and soils comprise solid liquids and gases, so that, e.g. processes of sorption/retardation occur within these features and do not have to be listed in ODEs.
12,X	Processes operating from "elsewhere" to components of the reference biosphere case indicate where uncontaminated material (water and solids) enter the system.
X,12	Processes operating from LDEs to "elsewhere" indicate potential for losses of radionuclides to outside the local biosphere area.
1,2; 1,7	Radionuclide release into the local aquifer and/or surface water can be accompanied by a flux of water and suspended sediment.
2,1; 2,12	Loss of radionuclides from the local aquifer back to the aquifer pathway from depth is pessimistically ignored, as are diffusive losses to elsewhere.
2,3; 3,4; 4,5	"Capillary rise" also captures advective processes, such as variation in the depth of the water table, intermittent perched saturation, etc.
3,6; 6,3	Connectivity in the reference biosphere case is between the local aquifer and the river.
3,7; 4,7	Potential for interflow (lateral flow)/discharge/erosion from the deep soil and variably saturated zone to the river is ignored in the reference biosphere case as it is expected to be small relative to erosive transfer from the topsoil and discharge via the local aquifer.
5,7	Similarly, potential for interflow and associated suspended sediment from the topsoil to surface water are ignored.
7,8	Potential radionuclide losses due to degassing from surface water are conservatively ignored; losses and/or exposures arising directly from irrigation spray are considered to be negligible; evaporation from surface water is also considered negligible in comparison to the overall water balance.
8,5; 8,7; 8,9	Deposition of suspended particles (e.g. dust) from atmosphere to soil, surface water and plants is ignored; soil contamination of plants is included in 5,9.
8,10	Inhalation of gas and suspended dust is considered a small contributor to potential radionuclide uptake by livestock in comparison to ingestion (drinking water, soil and feed) and is ignored.

Position	Comment
9,4	Although roots will extend into the deep soil, interaction between crops and soil is considered to be dominated by topsoil.
9,5; 10,8; 11,8	Return transfers from animals, crops and humans to soils and sediments are implicitly included in equilibrium assumptions. The associated processes of uptake and return are fast and unimportant relative to other processes affecting radionuclide retention in soils and the atmosphere.
2,11; 7,11	Potential exposures arising from bathing (swimming and washing) in water are ignored as being relatively unimportant.
5,11; 6,11	Inadvertent ingestion of topsoil and river bed sediment are ignored as being relatively unimportant; inadvertent ingestion of external soil contamination on crops is included (see 5,9).
9,12; 10,12; 11,12	Losses due to export of crops and livestock (i.e. removal of produced foodstuffs from the local area) and movement of people to outside of the system are pessimistically ignored.

4.1.1.1 Features, events and processes for transport in the biosphere

Features between which radionuclide transfer requires dynamical modelling in the biosphere can be conceived as compartments. When modelling the transport of radionuclides between compartments, it is important to recognise that transport can take place in solution (Fig. 4-2) and with the fluxes of solid materials (Fig. 4-3). It is therefore important to distinguish between radionuclides in solution and those associated with solid materials. Given that environmental concentrations will be at trace levels, it is possible to model the partitioning between solution and solid materials with an equilibrium approach (K_d concept); see discussion in Metcalfe et al. (2023).

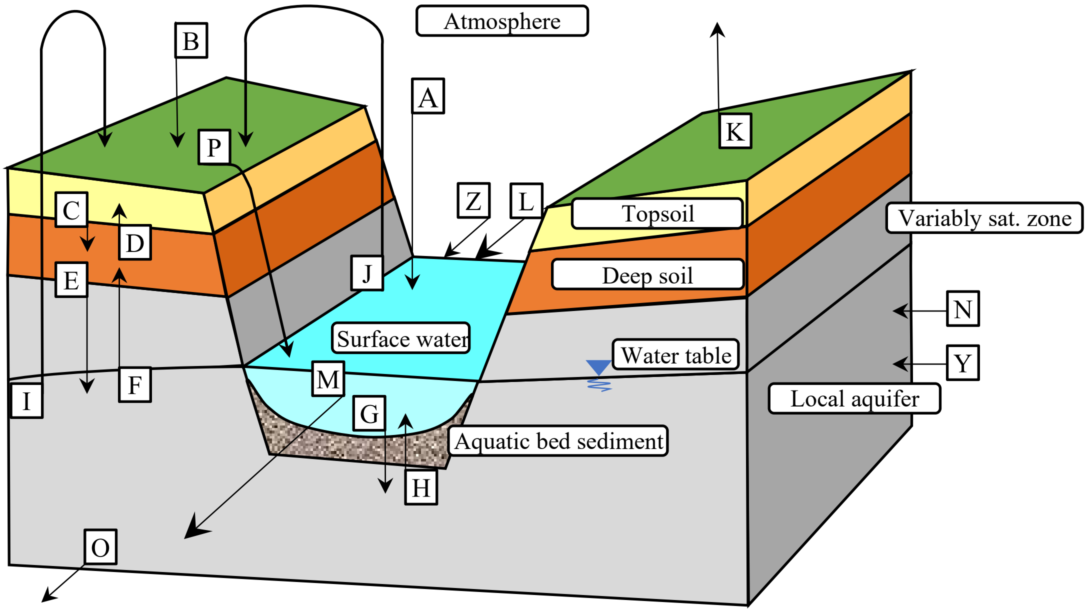

Fig. 4-2: Conceptualisation of the principal water fluxes for biosphere modelling

Not to scale. The figure is generic and includes processes relevant to the reference and alternative cases. Nomenclature for Fig. 4-2:

A Precipitation: → water surface
B Precipitation: → soil surface
C Infiltration: topsoil → deep soil
D Upward movement: deep soil → topsoil (capillary rise)
E Infiltration: deep soil → variably saturated zone → local aquifer
F Upward movement: local aquifer → variably saturated zone → deep soil (capillary rise)
G Infiltration: surface water → local aquifer (via bed sediment)
H Discharge: local aquifer → surface water (via bed sediment)
I Irrigation with groundwater from the local aquifer
J Irrigation with surface water and flooding
K Evapotranspiration: evaporation loss to atmosphere (soil/water surface), transpiration loss from plants
L Surface water throughput (inflow from upstream)
M Surface water throughput (outflow) and other losses (e.g. extraction for use outside the biosphere section)
N Groundwater throughput (inflow) from depth or from shallow groundwater upgradient
O Groundwater throughput (outflow from the local aquifer) and other losses (e.g. extraction for use outside the biosphere section)
P Surface runoff (overland flow)
Y Entry of water-bearing radionuclides from depth to the local aquifer
Z Direct discharge of water-bearing radionuclides to surface water from depth

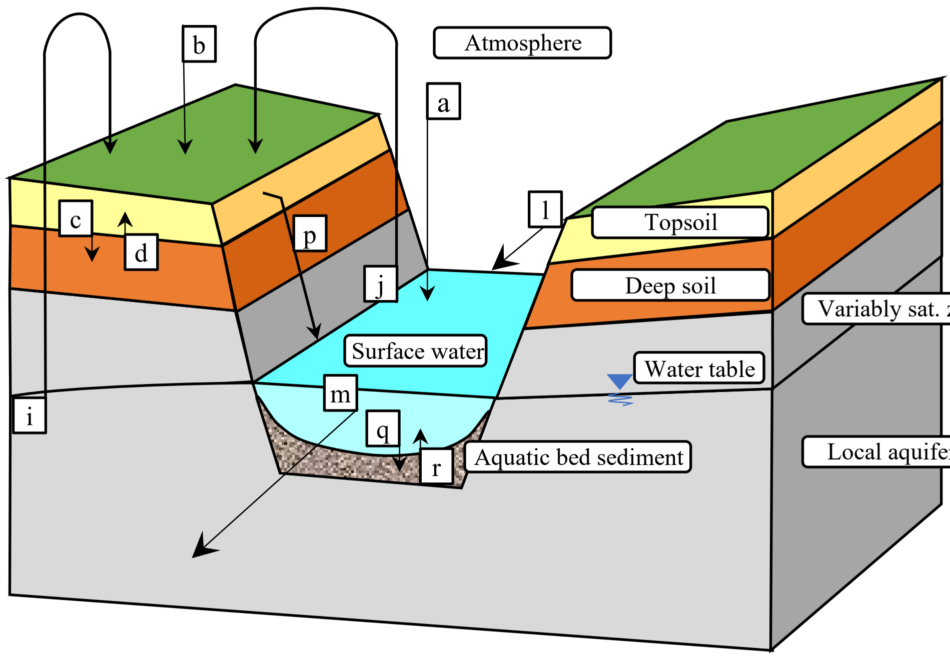

Fig. 4-3: Conceptualisation of the principal solid material fluxes for biosphere modelling

Not to scale. The figure is generic and includes processes relevant to the reference and alternative cases. Nomenclature for Fig. 4-3:

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

Diffusion in the aqueous phase between components of varying concentrations may also play a role, provided its contribution is not outweighed by advective/dispersive transport and that the mathematical formulation of diffusive transport does not conflict with the assumption of homogenous concentrations within the compartments and with the lower limit for timescales of interest (the annual cycle). As a result, only vertical diffusion processes between the local aquifer through to the soil and sediment compartments are considered.

Some radionuclides may also enter the gas phase in the biosphere. Guillemot et al. (2024) identifies that C-14 can be released from soil at rooting depth and be lost from the local area via the gas phase. The inclusion of a loss term for the soil at rooting depth allows this process to be included for C-14.

The soil at rooting depth is considered to be well mixed over relatively small timescales (in comparison to radionuclide release rates from the geological barrier). The local aquifer is treated as a homogenous unit. Similarly, the lower horizons and the variably saturated zone between the aquifer and the rooting depth are each treated as a single entity. In the aquatic environment, a distinction is made between the surface water and bed sediments.

4.1.1.2 Features, events and processes for exposure pathways

Radiological doses are characterised as the exposure of individuals to the environmental concentrations of radionuclides in the biosphere. This report adopts the definition of the effective dose given in ICRP Publication 103 (ICRP 2007). The exposure pathways considered are:

- intake of contaminated foodstuffs;
- inhalation of airborne radionuclides; and
- exposure to external irradiation from contaminated environmental media.

As mentioned in Chapter 2, some assumptions are made to ensure that the exposure of the average individual is not underestimated. This is achieved by assuming that (i) all food consumed is grown locally (ensuring no dilution of intake of contaminants) and that (ii) the average individual resides in the region of highest concentration during the entire year, thus receiving the highest doses from inhalation and external irradiation. A self-sufficient agricultural community would have a relatively high value for calorific intake, one that is commensurate with the strenuous working conditions of agricultural workers.

In order to simplify the model, the number of different foodstuffs consumed and environmental exposure pathways considered can be generalised to the following:

- consumption pathways:
  - drinking water;
  - freshwater fish;
  - meat (beef and chicken), eggs, milk and dairy products;
  - grain, green vegetables, root vegetables, fruit;
- environmental exposures:
  - external irradiation;
  - inhalation of radioactive dust or radioactive gas having escaped from the rooting depth.

One further reason for this generalisation is that the database for food consumption is sparse and often contradictory. Best-estimate parameters for a small number of generic consumption pathways are therefore more reliable. For an agricultural lifestyle, only limited time would be spent close to bodies of water, so inhalation of gas and aerosols from surface water can be neglected. The flow rate in the river means that these exposure pathways would be negligible in any case.

All radionuclides removed from the biosphere compartments by the action of radiation exposure are assumed to be recycled annually so that the exposures are not diminished by the pathways acting as external sinks to the transport model.

Fig. 4-4 shows the network of exposure pathways considered. Radionuclide concentrations in crops and other vegetation arise from:

- root uptake;
- irrigation and foliar absorption; and
- soil particles on external surfaces.

Similarly, concentrations of contaminants in animal tissues and other products arise from:

- drinking water consumption;
- intake of contaminated foodstuffs;
- the direct intake of contaminated soils.

Only external irradiation and drinking water pathways (from the local aquifer or from the surface water compartment) are directly connected to radionuclide concentrations in the biosphere compartments that are dynamically modelled. The other exposure pathways consider intermediate FEPs and associated equilibrium assumptions, as illustrated in Fig. 4-4.

The modelling approach defined here is designed to be generic and allows for the definition of multiple distinct soil areas (topsoil and deep soil), e.g. with different crops. Where multiple soil areas are included, each crop (including pasture) is assumed to be grown in a particular area and so the relevant topsoil compartment is used. External irradiation, dust and gas inhalation are treated by averaging (weighted by area) over all the topsoil areas. For the reference biosphere, warmer-drier climate and drained farmland cases, rotation and uniform irrigation/flooding, etc., are assumed in such a way as to represent a single soil area. For the cold climate case (discussed further in Section 4.1.2), the area cultivated on a small scale is represented separately. This is further discussed in Section 4.2.

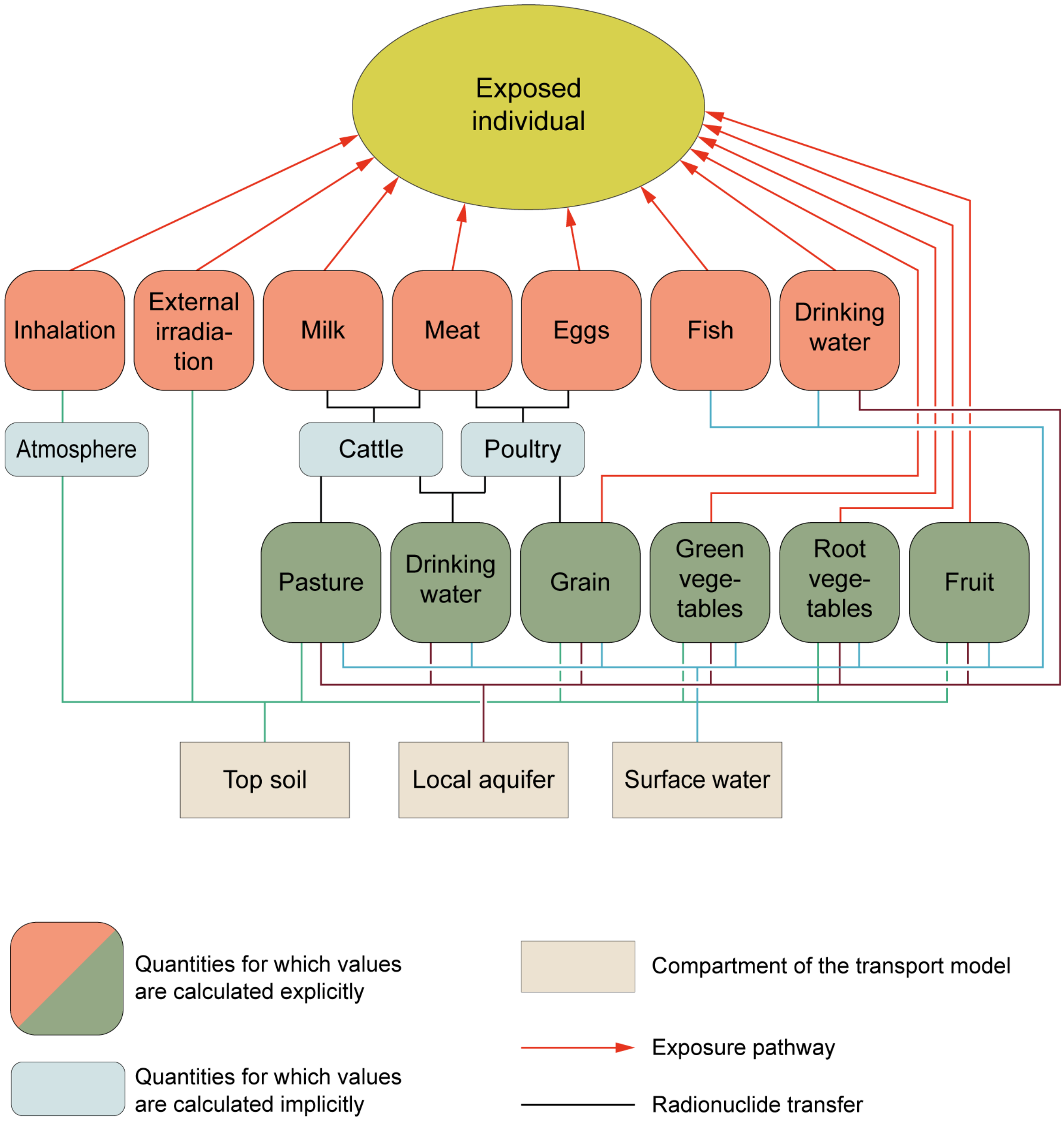

Fig. 4-4: Exposure pathways represented in the biosphere model

4.1.2 Alternative biospheres

The overall structure of the biosphere remains consistent between the reference and alternative biosphere systems that are carried through to assessment, with groundwater potentially carrying radionuclides from the repository and discharging them to unconsolidated near-surface Quaternary sediments in a valley in Northern Switzerland. However, the configuration of the biosphere can differ between the reference and alternative cases. The differences for each of the alternative cases relating to radionuclide behaviour and potential exposure are described below.

Warmer-drier climate case: The configuration for this case is identical to that for the reference biosphere case. It can be distinguished through parameterisation, especially for hydrogeological-related parameters. Potential exposure pathways for the warmer-drier climate case remain the same as for the reference biosphere case.

Cold climate case: The cold climate case is notably different from the reference biosphere case in the following ways:

- The presence of permafrost prevents a groundwater pathway connection between the local aquifer and soils.
- Although not a true organic soil, the topsoil is taken to have a higher degree of organic matter content compared to the reference biosphere case due to a greater degree of saturation and slower degree of organic matter degradation in cold climate conditions.
- There is a relatively small area devoted to growing a limited range of crops during the short growing season; the wider valley area is used for grazing by livestock but is not actively cultivated.
- Outside the relatively small area used for horticultural production, the soils are thinner than those considered in the reference biosphere case.
- Even accounting for a smaller community group, the low productivity associated with a cold climate context means that a notable proportion of the energy/food requirements for the local population will have to be derived from elsewhere.

The main conceptual points of difference from the reference biosphere case are illustrated in Fig. 4-5.

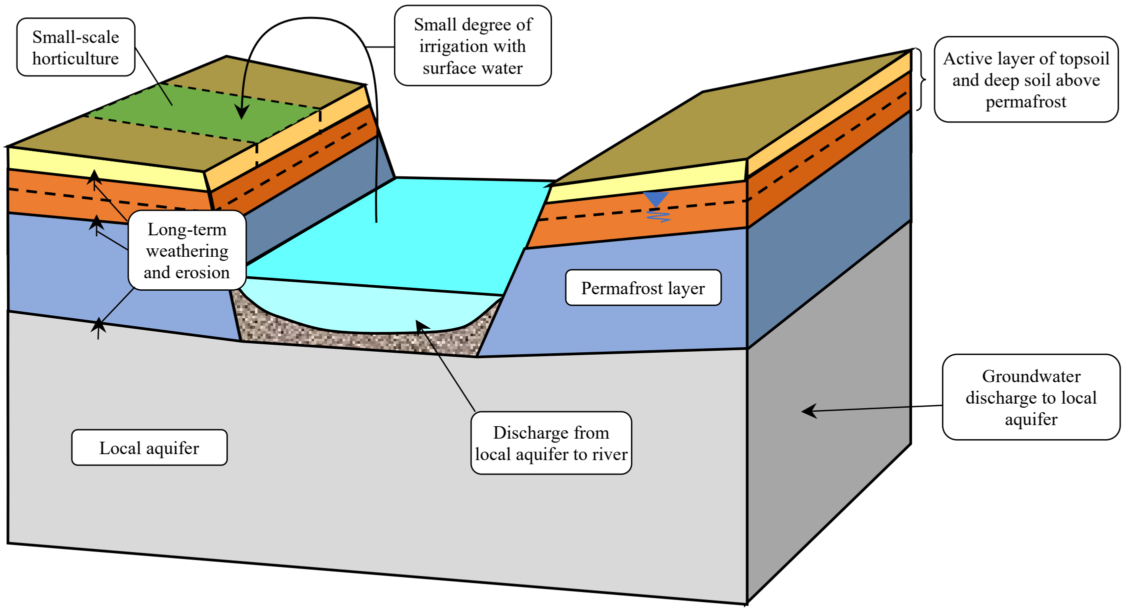

Fig. 4-5: Conceptual differences for the cold climate in comparison to the reference biosphere

Not to scale. The figure does not show all of the water and solid transfers; the emphasis is on illustrating important distinctions between the cold climate and the reference biosphere.

Potential exposure pathways considered for the cold climate case are:

- external irradiation and inhalation of soil-derived dust and gases from occupancy of the soil areas during the summer months, in particular;
- ingestion of drinking water drawn from surface water;

- ingestion of meat products from animals herded over the valley:
  - animals would obtain their feed from the potentially contaminated region;
  - animals would obtain their drinking water from the surface water in this section of valley;
- ingestion of crops grown through small-scale agriculture:
  - a limited range of relevant crops (green vegetables and root vegetables, but no cereal crops or fruit);
  - the crops would only provide a fraction of the vegetable intake required by the local community;
- ingestion of wild foods foraged from the valley outside of the small agricultural area:
  - represented as fruit (e.g. berries) and providing a fraction of the fruit intake requirement of the local community;
- ingestion of fish caught from the surface water during the summer months, although this would only provide a fraction of the fish intake requirement for the local community.

Drained farmland case: The drained farmland case represents a section of valley within which the water table would naturally lie closer to the soil surface compared to the reference biosphere case. The degree of saturation of soils is controlled through field drains and ditches to provide improved agricultural conditions. The overall configuration of the valley system is the same as in the reference biosphere case. However, the position of the water table within the deep soil means that connectivity and water-mediated transfers differ, as summarised below:

- Those unconsolidated Quaternary sediments referred to as the "variably saturated zone" in the reference biosphere case are taken to be fully saturated and effectively part of the local aquifer; the river is situated within this layer.
- As part of the local aquifer, there is potential for some discharge of groundwater carrying radionuclides from the deep geological repository to the upper part of the shallow local aquifer.
- Along the length of the valley section, there is potential for some direct discharge of groundwater from the upper part of the local aquifer to the river.
- The degree of saturation of the deep soil is increased compared to the reference biosphere case to reflect the higher water table, and there is a transfer of water from the deep soil to the surface water via field drains and/or ditches.
- Although not a true organic soil, the topsoil is considered to have a higher degree of organic matter content compared to the reference biosphere case due to the higher degree of saturation that will have occurred prior to drainage for improved agricultural usage.
- There is an increased potential for advective transport of radionuclides upwards to the topsoil via capillary rise, and through seasonal and episodic variations in groundwater levels.
- There is potential for transfer of water and river sediments to land through periodic flooding.
- The range of crops grown in the area where the water table is closer to the soil surface is considered to be limited to green and root vegetables, with cereals and fruit assumed to be grown elsewhere.

The main conceptual points of difference from the reference biosphere case are illustrated in Fig. 4-6.

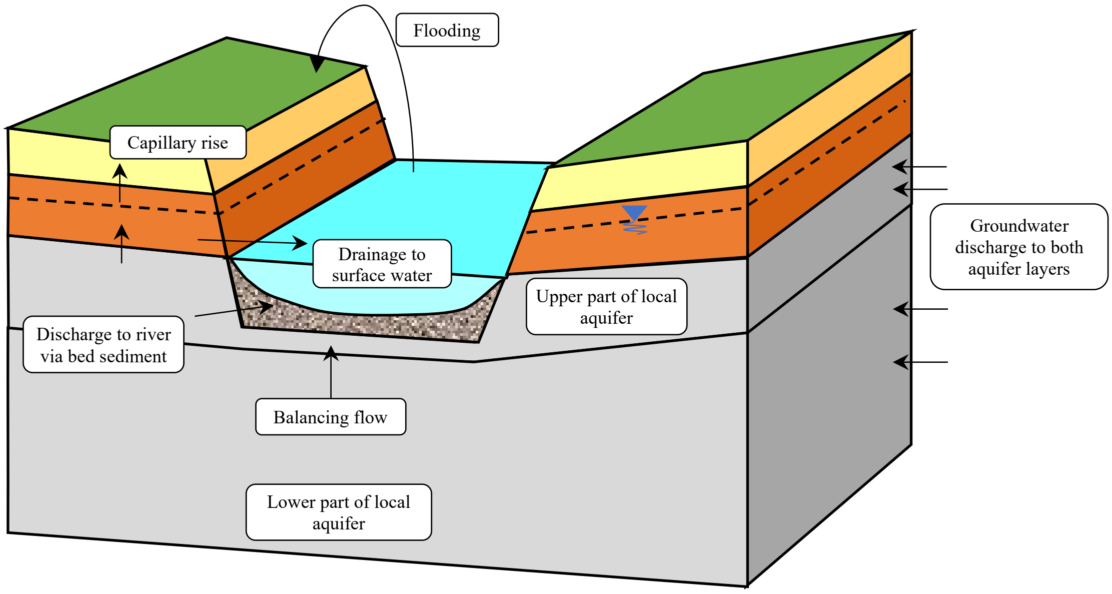

Fig. 4-6: Conceptual differences between the drained farmland and the reference biosphere

Not to scale. The figure does not show all of the water and solid transfers; the emphasis is on illustrating important distinctions between the drained farmland and the reference biosphere.

The potential exposure pathways considered for the drained farmland case are as follows:

- external irradiation and inhalation of soil-derived dust and gases during occupancy of the potentially contaminated soil area (as in the reference biosphere case);
- ingestion of drinking water drawn from groundwater, which, in turn, is drawn from the local aquifer (from both compartments below the deep soil);
- ingestion of crops grown in the valley area:
  - a limited range of crops would be grown in the potentially contaminated area (green vegetables and root vegetables);
  - the remaining crops (cereals, fruit) are assumed to be grown outside of the potentially contaminated area;
- ingestion of meat products from animals reared in the valley:
  - cows would obtain their feed from pastures in the potentially contaminated valley area;
  - cows would obtain their drinking water from the surface water;
- ingestion of fish caught from the river (as in the reference biosphere case).

4.2 Mathematical model

In total, six main types of compartments (soil at rooting depth, local aquifer, variably saturated zone above the aquifer, lower soil horizons, surface water and bed sediments) together with some ancillary compartments are considered for modelling the transport of radionuclides within the biosphere. These are shown in Fig. 4-7. The names of the compartments have distinct meanings and are used in the mathematical representation for identification purposes and for transfer purposes between compartments; Fig. 4-2 summarises the respective nomenclature.

The ancillary compartments represent sources of water (groundwater, upstream river, atmosphere), potential radionuclide sources to the biosphere (contaminated groundwater, contaminated upstream river), and can receive radionuclides that leave the local region (atmosphere and elsewhere). These are important components of the model, but do not require explicit compartments within the mathematical model.

The compartmentalisation in Fig. 4-7 implies that, e.g., the same irrigation or erosion regime applies to the entire area. In order to allow for different regimes within the local area, the topsoil and deep soil can be subdivided into several separate smaller areas. Each of these smaller areas may then have different soil properties or irrigation regimes. This subdivision is not needed for the reference, warmer-drier climate or drained farmland cases, but is used in the cold climate case to distinguish the small-scale, cultivated area from the larger pastural areas.

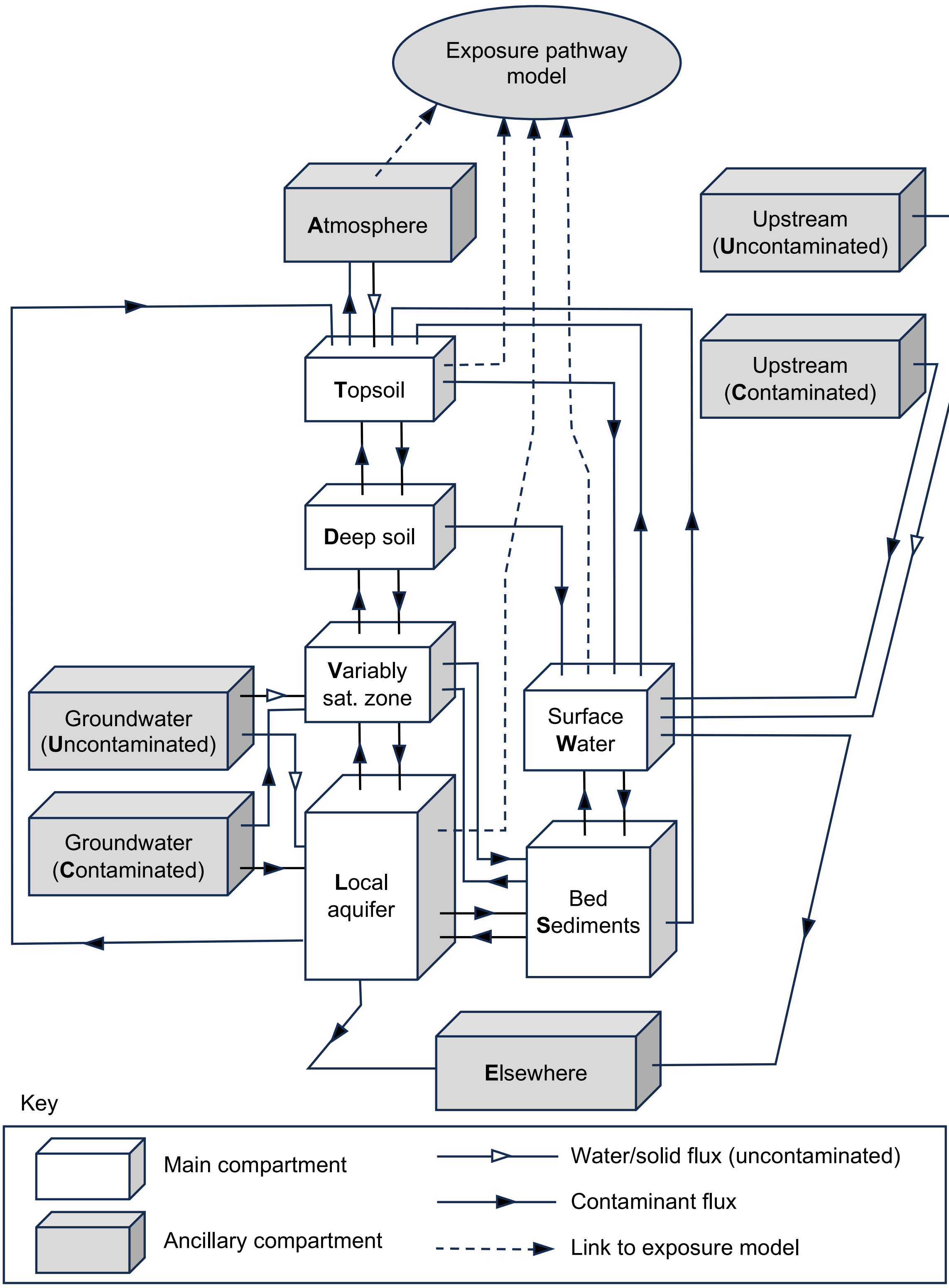

Fig. 4-7: Structure of the compartment model of the biosphere

Includes transfers for reference and alternative biosphere cases. Radionuclide retention within the main compartments is explicitly modelled, whereas the ancillary compartments contribute to the overall water/solid balances and provide a route for radionuclides to escape from the system (e.g. flow downstream and/or losses into the atmosphere).

Tab. 4-2: Nomenclature of model compartments

The index *k* stands for a given soil area.

Compartment	Symbol	Description
Dynamic compartments		
Local aquifer	L	Near-surface geological media supporting groundwater flow, possibly associated with bodies of surface water
Variably saturated zone	V	Near-surface geological media above the local aquifer
Deep soil	D_k	Soil horizons between the local aquifer and the rooting depth of crops for soil area *k*
Topsoil	T_k	Soil horizons containing the roots of crops for soil area *k*
Surface water	W	Springs, streams, rivers, ponds, lakes, reservoirs
Aquatic bed sediment	S	Solid material forming the bed of bodies of surface water (when distinguished from the aquifer material)
Ancillary compartments		
Contaminated	C	Source of contaminated water and suspended solids to the biosphere
Uncontaminated	U	Source of uncontaminated water and suspended solids to the biosphere
Atmosphere	A	Source of uncontaminated precipitation
Elsewhere	E	Compartment acting as a sink for runoff and outflow

4.2.1 Radionuclide releases to the biosphere

Biosphere modelling determines the BDCFs based on a unit release rate (1 Bq a^{-1}) for each radionuclide. Releases can be directed to the local aquifer (L), variably saturated zone (V) or surface water (W) depending on fractions defined as Rel_L, Rel_V and Rel_W, respectively.

4.2.2 General mass balance equation

The transport of radionuclides between the main compartments is modelled using mass balance considerations between all compartments. The amount of radionuclide *N* in the i^{th} compartment is denoted by N_i. The transfer interactions are then denoted by a set of fractional transfer rates from this compartment to the other *j* compartments in the system λ_{ij} and to this compartment from all the others λ_{ji}. The rate of change of the content of compartment *i* is therefore:

$$\frac{dN_i}{dt} = \left(\sum_{j\neq i} \lambda_{ji} N_j + \sigma_{MN} \lambda_N M_i + S_{N,i}\right) - \left(\sum_{j\neq i} \lambda_{ij} N_i + \lambda_N N_i\right) \qquad [Bq\ a^{-1}] \qquad (1)$$

with

N_j *[Bq]* inventory of nuclide *N* in compartment *j*;

M_i *[Bq]* amount of the precursor radionuclide of *N* in compartment *i*;

λ_{ij} *[a^{-1}]* fractional transfer rate from compartment *i* to *j*;

λ_N *[a^{-1}]* decay constant of radionuclide *N*;

σ_{MN} *[-]* branching ratio for decay from contaminant *M* to *N*; and

$S_{N,i}$ *[Bq a^{-1}]* external source term of radionuclide *N* into compartment *i*.

Note that the ingrowth term is $\lambda_N M_i$ because activity units (of radionuclide *N*) are used.

Distributions within compartments are taken to be homogeneous, either because there is relatively rapid mixing (e.g. within the surface water), or because finer resolution is not needed when evaluating potential exposures (e.g. variability in soils is averaged by agricultural practice and human behaviour).

4.2.3 Representation of intercompartmental transfers

4.2.3.1 General

The parameterisation of the fractional transfer rates λ_{ij} takes account of site-specific transport characteristics of the surface environment. The model allows a range of biosphere types to be represented; only the numerical values of the λ_{ij} will change when representing the differences in the site characteristics.

For each transfer process represented in the model, the transfer coefficient *k* between two compartments is defined as:

$$\lambda_{ij}^{(k)} = \frac{1}{N_i}\left(\frac{dN_{ij}}{dt}\right)^{(k)} \qquad [a^{-1}] \qquad (2)$$

where

$\left(\frac{dN_{ij}}{dt}\right)^{(k)}$	*[Bq a^{-1}]*	amount of nuclide *N* moved from compartment *i* to *j* in unit time by process *k*.

These transfers relate to the migration of radionuclides, and these must be related to the processes identified in Section 3.1, which describe the fluxes of water, solid material and gas between compartments. Additionally, the dynamic exchange of contaminants by diffusion must also be considered. This requires the use of the compartmental solid-liquid distribution coefficient to determine the amount of contaminants in solution compared to the amount associated with solid material in the compartment.

The general form for the transfer of contaminants from compartment *i* to compartment *j* is given by:

$$\lambda_{ij} = \frac{1}{\theta_i + (1-\varepsilon_i)\rho_i K_{d,i}}\left(\frac{F_{ij} + K_{d,i}M_{ij}}{l_i A_i} + D_{ij}\right) \qquad [a^{-1}] \qquad (3)$$

with

F_{ij}	*[m^3 a^{-1}]*	water flux from compartment *i* to compartment *j*;
M_{ij}	*[kg a^{-1}]*	solid material flux from compartment *i* to compartment *j*; and
D_{ij}	*[a^{-1}]*	effective (vertical) diffusion rate for dissolved radionuclides from compartment *i* to compartment *j*.

These are linked to the physical properties of the system:

l_i	*[m]*	depth/thickness/length of compartment *i*;
A_i	*[m²]*	surface (plan) area of compartment *i*;
θ_i	*[-]*	volumetric moisture content of compartment *i*;
ε_i	*[-]*	porosity of compartment *i*;
ρ_i	*[kg m⁻³]*	solid (grain) density of material in compartment *i*; and
$K_{d,i}$	*[m³ kg⁻¹]*	solid-liquid distribution coefficient in compartment *i*.

These expressions form the basis for the transport model, which is therefore principally defined based on water, F_{ij}, solid material, M_{ij}, and diffusive, D_{ij}, fluxes between compartments. The first factor represents the fraction of the radionuclide inventory that is in liquid form, whereas the two terms in the parentheses represent the turnover rate of water or solved radionuclides with respect to advection and diffusion, respectively.

4.2.3.2 Water fluxes

The water fluxes included in the model are illustrated in Fig. 4-8 (for a single soil area), while the processes represented are defined in Tab. 4-3.

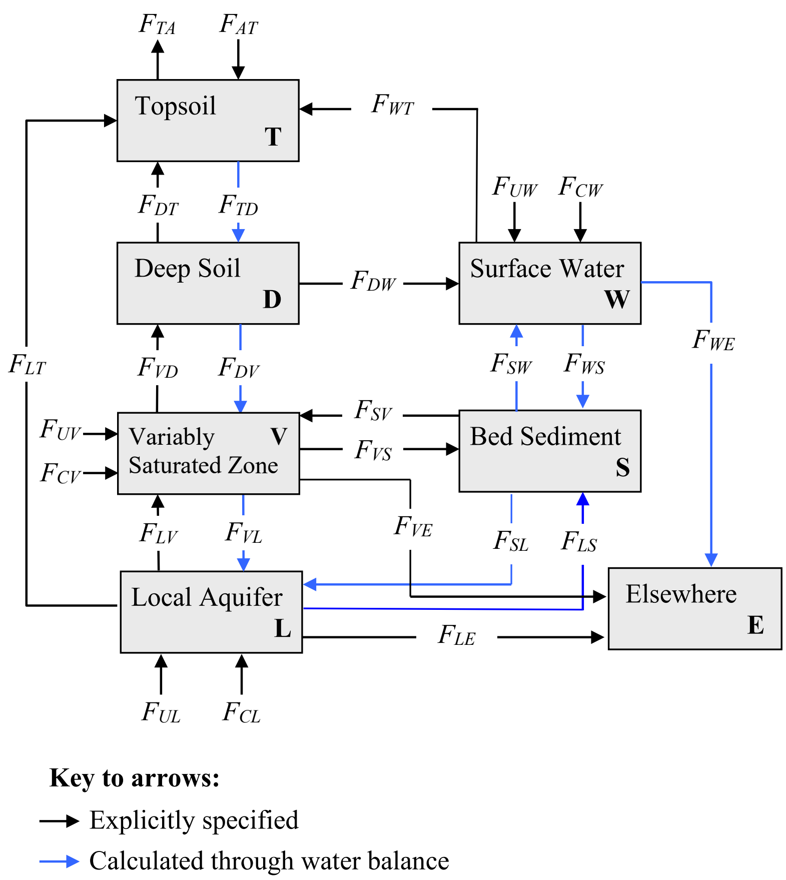

Fig. 4-8: Intercompartmental water fluxes

Situation for a model with a single soil area.

Tab. 4-3: Nomenclature of water fluxes

Water fluxes are volumetric, $[m^3 \, a^{-1}]$

Symbol	Description
$F_{A,Tk}$	Precipitation minus runoff for soil area *k*
$F_{Tk,A}$	Evapotranspiration for soil area *k*
$F_{L,Tk}$	Irrigation with groundwater (from local aquifer) for soil area *k*
$F_{W,Tk}$	Flooding and irrigation with surface water for soil area *k*
$F_{Tk,Dk}$	Percolation from topsoil to deep soil for soil area *k*
$F_{Dk,Tk}$	Water flux from deep soil to topsoil (e.g. capillary rise) for soil area *k*
$F_{Dk,W}$	Water flux from deep soil to surface water (e.g. drainage ditches) for soil area *k*
$F_{Dk,V}$	Percolation from deep soil to variably saturated zone for soil area *k*
$F_{V,Dk}$	Water flux from variably saturated zone to deep soil (e.g. capillary rise, dispersive mixing) for soil area *k*
$F_{U,V}$	Flux of uncontaminated groundwater into variably saturated zone
$F_{C,V}$	Discharge of contaminated groundwater into variably saturated zone
$F_{V,S}$	Water flux from variably saturated zone to bed sediments
$F_{S,V}$	Water flux from bed sediments to variably saturated zone
$F_{V,L}$	Percolation/mixing from variably saturated zone to local aquifer
$F_{L,V}$	Water flux from local aquifer to variably saturated zone (e.g. dispersive mixing)
$F_{U,L}$	Flux of uncontaminated groundwater into local aquifer
$F_{C,L}$	Discharge of contaminated groundwater into local aquifer
$F_{L,S}$	Net water flux from local aquifer to bed sediments
$F_{S,L}$	Net water flux from bed sediments to local aquifer
$F_{S,W}$	Water flux from bed sediments to surface water
$F_{W,S}$	Water flux from surface water to bed sediments
$F_{U,W}$	Flux of uncontaminated water into surface water (mainly from upstream surface water, but also precipitation)
$F_{C,W}$	Flux of contaminated water into surface water
$F_{V,E}$	Water flux from variably saturated zone to sink (out of the model area)
$F_{W,E}$	Water flux from surface water to sink (out of the model area)
$F_{L,E}$	Water flux from local aquifer to sink (out of the model area)

Expressions for determining the specified water fluxes from the characteristics of the biosphere are given below and should not be negative[6].

The flux of water from the atmosphere to the topsoil for soil area k, $F_{A,Tk}$, is given by:

$$F_{A,Tk} = (d_{PPT} - d_{RO})A_{f,k} \qquad [m^3\ a^{-1}] \qquad (4)$$

where

A_f	$[m^2]$	is the surface area of the biosphere region, with separate values for each soil area denoted $A_{f,k}$;
d_{PPT}	$[m\ a^{-1}]$	is the mean annual precipitation rate; and
d_{RO}	$[m\ a^{-1}]$	is the mean annual rate of surface runoff (overland flow).

The flux of water from the topsoil to the atmosphere, $F_{Tk,A}$, is given by:

$$F_{Tk,A} = d_{ETP}A_{f,k} \qquad [m^3\ a^{-1}] \qquad (5)$$

where

d_{ETP}	$[m\ a^{-1}]$	is the mean annual evapotranspiration rate.

The flux of water from the local aquifer to the topsoil, $F_{L,Tk}$, is given by:

$$F_{L,Tk} = Irri_{L,k}A_{f,k} \qquad [m^3\ a^{-1}] \qquad (6)$$

where

$Irri_L$	$[m\ a^{-1}]$	is the mean annual rate of irrigation with groundwater from the local aquifer; separate values for each soil area are denoted $Irri_{L,k}$.

The flux of water from the surface water to the topsoil, $F_{W,Tk}$, includes flooding and is given by:

$$F_{W,Tk} = Irri_{W,k}A_{f,k} \qquad [m^3\ a^{-1}] \qquad (7)$$

where

$Irri_W$	$[m\ a^{-1}]$	is the mean annual rate of transfer from surface water to topsoil (including irrigation and flooding); separate values for each soil area are denoted $Irri_{W,k}$.

The flux of water from the deep soil to the topsoil, $F_{Dk,Tk}$, is given by:

$$F_{Dk,Tk} = d_{capil}A_{f,k} \qquad [m^3\ a^{-1}] \qquad (8)$$

where

d_{capil}	$[m\ a^{-1}]$	is the mean annual rate of capillary rise from deep soil to topsoil.

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6 This precondition is checked by the code.

The flux of water from the topsoil to the deep soil, $F_{Tk,Dk}$, is calculated according to the flux required to balance the topsoil compartment and is given by:

$$F_{Tk,Dk} = F_{A,Tk} + F_{L,Tk} + F_{W,Tk} + F_{Dk,Tk} - F_{Tk,A} \quad [m^3\ a^{-1}] \quad (9)$$

The flux of water from the deep soil to the variably saturated zone, $F_{Dk,V}$, is calculated according to the flux required to balance the deep soil compartment and is given by:

$$F_{Dk,V} = F_{Tk,Dk} + F_{V,Dk} - F_{Dk,Tk} - F_{Dk,W} \quad [m^3\ a^{-1}] \quad (10)$$

The flux of water from the variably saturated zone to the aquifer, $F_{V,L}$, is calculated according to the flux required to balance the variably saturated zone compartment and is given by:

$$F_{V,L} = F_{U,V} + F_{C,V} + F_{L,V} + \sum_k \left(F_{Dk,V} - F_{V,Dk}\right) + F_{S,V} - F_{V,S} - F_{V,E} \quad [m^3\ a^{-1}] \quad (11)$$

The net water fluxes between the local aquifer and bed sediment compartments are determined by the water balance for the local aquifer compartment:

$$F_{L,S} = \max\left\{F_{U,L} + F_{C,L} - F_{L,E} + F_{V,L} - F_{L,V} - \sum_k \left(F_{L,Tk}\right), 0\right\} \quad [m^3\ a^{-1}] \quad (12)$$

$$F_{S,L} = \max\left\{\sum_k \left(F_{L,Tk}\right) + F_{L,V} - F_{V,L} - F_{U,L} - F_{C,L} + F_{L,E}, 0\right\} \quad [m^3\ a^{-1}] \quad (13)$$

Similarly, the net water fluxes between the bed sediment and the surface water are determined by the water balance for the bed sediment compartment and expressed either as an upward ($F_{S,W}$) or a downward flux ($F_{W,S}$):

$$F_{S,W} = \max\left\{F_{L,S} + F_{V,S} - F_{S,L} - F_{S,V}, 0\right\} \quad [m^3\ a^{-1}] \quad (14)$$

$$F_{W,S} = \max\left\{F_{S,L} + F_{S,V} - F_{L,S} - F_{V,S}, 0\right\} \quad [m^3\ a^{-1}] \quad (15)$$

The water flux from the surface water to elsewhere is given by:

$$F_{W,E} = F_{U,W} + F_{C,W} + F_{S,W} - F_{W,S} + \sum_k (F_{Dk,W} - F_{W,Tk}) \quad [m^3\ a^{-1}] \quad (16)$$

4.2.3.3 Solid material fluxes

The solid material fluxes included in the model are illustrated in Fig. 4-9, while the processes represented are defined in Tab. 4-4. Expressions for determining the specified fluxes of solid material from the characteristics of the biosphere are given below and should not be negative.

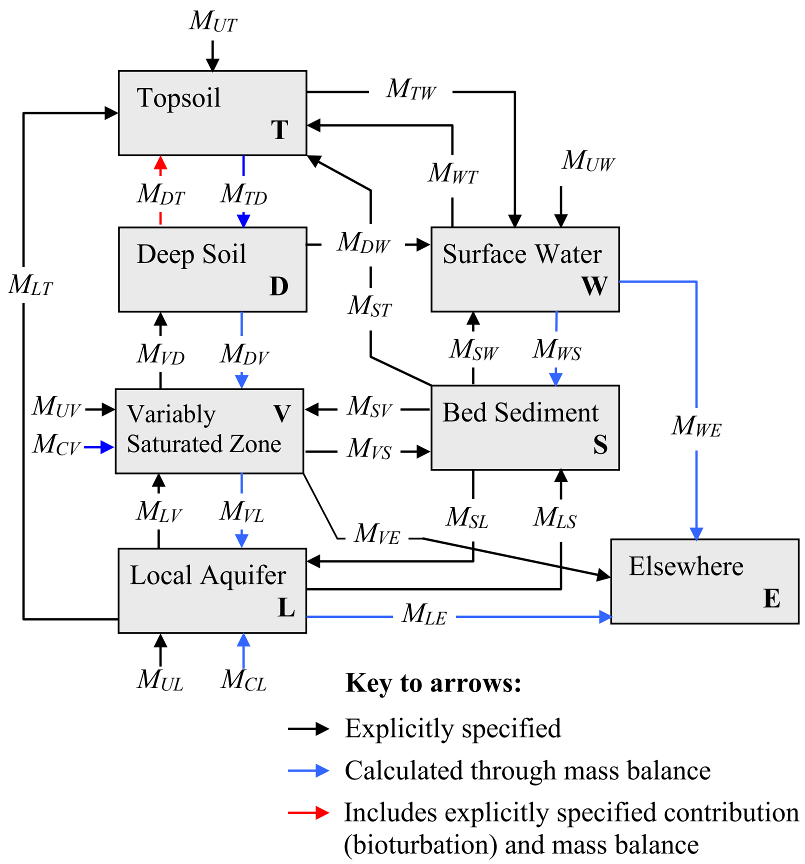

Fig. 4-9: Intercompartmental solid material fluxes

Situation for a model with a single soil area.

Tab. 4-4: Nomenclature of solid material fluxes

Solid material fluxes are based on mass, *[kg a⁻¹]*

Symbol	Description
$M_{L,Tk}$	Solid material flux (suspended solid material) by irrigation with groundwater from local aquifer for soil area *k*
$M_{W,Tk}$	Solid material flux (suspended solid material) from surface water to topsoil by flooding and irrigation for soil area *k*
$M_{Tk,W}$	Solid material flux from topsoil to surface water by erosion for soil area *k*
$M_{Tk,Dk}$	Solid material flux from topsoil to deep soil (e.g. bioturbation and water-mediated transport) for soil area *k*
$M_{Dk,Tk}$	Solid material flux from deep soil to topsoil (e.g. bioturbation) for soil area *k*
$M_{Dk,W}$	Solid material flux from deep soil to surface water for soil area *k*
$M_{Dk,V}$	Solid material flux from deep soil to variably saturated zone (e.g. percolation) for soil area *k*
$M_{V,Dk}$	Solid material flux from variably saturated zone to deep soil for soil area *k*
$M_{U,V}$	Flux of uncontaminated solid material into variably saturated zone
$M_{C,V}$	Balancing flux of uncontaminated solid material into variably saturated zone
$M_{V,S}$	Solid material flux from variably saturated zone to bed sediments
$M_{S,V}$	Solid material flux from bed sediments to variably saturated zone
$M_{V,L}$	Solid material flux from variably saturated zone to local aquifer
$M_{L,V}$	Solid material flux from local aquifer to variably saturated zone
$M_{U,L}$	Flux of uncontaminated solid material into local aquifer
$M_{C,L}$	Balancing flux of uncontaminated solid material into local aquifer
$M_{L,S}$	Solid material flux from local aquifer to bed sediments
$M_{S,L}$	Solid material flux from bed sediments to local aquifer
$M_{V,E}$	Solid material flux from variably saturated zone to sink (includes additional fluxes used for mass balance reasons so that the dimensions of the variably saturated zone compartment stay constant in case of net deposition)
$M_{L,E}$	Solid material flux from local aquifer to sink (includes additional fluxes used for mass balance reasons so that the dimensions of the local aquifer compartment stay constant in case of net deposition)
$M_{W,S}$	Deposition of suspended solid material as bed sediments
$M_{S,W}$	Resuspension of bed sediments
$M_{S,Tk}$	Solid material flux from bed sediment to topsoil (e.g. dredging) for soil area *k*
$M_{U,W}$	Flux of uncontaminated solid material into surface water body (mainly suspended sediment from upstream surface water body) and external deposition on surface water (e.g. from erosion elsewhere)

Symbol	Description
$M_{U,Tk}$	External deposition on soil surface for soil area k (e.g. from erosion elsewhere)
$M_{W,E}$	Solid material flux from surface water to sink (e.g. suspended sediment and bedload)

Water fluxes ($F_{i,j}$) between compartments may carry suspended sediment material ($M_{i,j}^{susp}$), which is included in the solid material balance model according to:

$$M_{i,j}^{susp} = \alpha_i F_{i,j} \qquad [kg\ a^{-1}] \qquad (17)$$

where

α_i *[kg m^-3]* is the concentration of suspended solids in water/porewater.

The transfer of suspended solids is the only way by which solid material is transferred between the following compartments:

- uncontaminated water to surface water, $M_{U,W}$, in which case the suspended sediment concentration in the surface water is used, α_W;
- local aquifer to the topsoil, $M_{L,Tk}$;
- surface water to topsoil, $M_{W,Tk}$;
- deep soil to surface water, $M_{D,W}$ (except in the cold climate case where this also includes the flux of uncontaminated solid material to the topsoil to maintain mass balance in the deep soil);
- variably saturated zone to bed sediments, $M_{V,S}$;
- bed sediments to variably saturated zone, $M_{S,V}$;
- local aquifer to bed sediments, $M_{L,S}$;
- bed sediments to local aquifer, $M_{S,L}$;
- variably saturated zone to local aquifer, $M_{V,L}$.

The solid material flux from topsoil to surface water due to erosion for soil area k, $M_{Tk,W}^{erosion}$, is given by:

$$M_{Tk,W}^{erosion} = m_e A_{f,k} \qquad [kg\ a^{-1}] \qquad (18)$$

where

m_e *[kg m^-2 a^-1]* is the erosion rate; and

A_f *[m^2]* is the surface area of the biosphere region, with separate values for each soil area denoted $A_{f,k}$.

The flux of uncontaminated solid material to the topsoil due to deposition (e.g. due to hillslope erosion from the valley sides), $M_{U,Tk}^{deposition}$, is given by:

$$M_{U,Tk}^{deposition} = m_{dep} A_{f,k} \qquad [kg\ a^{-1}] \qquad (19)$$

where

m_{dep} *[kg m^-2 a^-1]* is the rate of sedimentation onto topsoil.

The flux of solid material from bed sediment to topsoil due to dredging practices is given by:

$$M_{S,Tk}^{dredging} = m_{SL,k} A_{f,k} \qquad [kg\ a^{-1}] \qquad (20)$$

where

m_{SL} *[kg m^-2 a^-1]* is the annual rate of transfer of sediment to agricultural land (per unit area of land not per unit area of bed sediment), separate values for each soil area denoted as $m_{SL,k}$.

The net solid material flux from each area of soil, $M_{net,k}$, can therefore be defined as[7]:

$$M_{net,k} = \left(m_e - m_{Dep} - m_{SL,k}\right) A_{f,k} \qquad [kg\ a^{-1}] \qquad (21)$$

The balance of erosion, deposition, dredging and suspended solid fluxes to the topsoil defines the solid material that has to be transferred from the deep soil to the topsoil (i.e. in cases of net erosion) or the solid material that has to be transferred from the topsoil to the deep soil (i.e. in cases of net deposition). The formulation is intended to be generic, however, in practice, there is net erosion from the topsoil in the environments considered (see Section 5.1), such that there is a net movement of mass vertically up through the system over time, representative of weathering.

The net mass change of the topsoil is assumed to be unaffected by bioturbation because the associated exchange between the topsoil and deep soil is considered to balance. The net mass change for the topsoil is also considered to be unaffected by suspended material, because the water exchanges balance and have the same suspended sediment concentration (see Section 5.1).

The uncontaminated solid material flux to the variably saturated zone, $M_{U,V}$, is given by:

$$M_{U,V} = \alpha_V F_{U,V} + (1 - f_{U,L}) \textstyle\sum_k M_{net,k} \qquad [kg\ a^{-1}] \qquad (22)$$

This includes both uncontaminated suspended material in uncontaminated groundwater entering the variably saturated zone (e.g. from an uncontaminated near-surface aquifer upgradient) and a fraction ($1-f_{U,L}$) of the uncontaminated solid material balancing net losses.

The uncontaminated solid material flux to the local aquifer, $M_{U,L}$, is given by:

$$M_{U,L} = \alpha_L F_{U,L} + f_{U,L} \textstyle\sum_k M_{net,k} \qquad [kg\ a^{-1}] \qquad (23)$$

This includes both uncontaminated suspended material in uncontaminated groundwater entering the local aquifer (e.g. from an uncontaminated near-surface aquifer upgradient) and a fraction ($f_{U,L}$) of the uncontaminated solid material balancing net losses.

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7 Note that while this preserves mass, material transferred between compartments is taken to adopt the properties (e.g. Kd and porosity) of the compartment that it is transferred to.

The solid material flux from the local aquifer to the variably saturated zone, $M_{L,V}$, is given by:

$$M_{L,V} = \alpha_L F_{L,V} + f_{U,L} \sum_k M_{net,k} \qquad [kg\ a^{-1}] \qquad (24)$$

The solid material flux from the variably saturated zone to the deep soil, $M_{V,Dk}$, is given by:

$$M_{V,Dk} = \alpha_V F_{V,Dk} + M_{net,k} \qquad [kg\ a^{-1}] \qquad (25)$$

The solid material flux from the deep soil to the topsoil includes bioturbation and is given by:

$$M_{Dk,Tk} = \alpha_D F_{Dk,Tk} + M_{net,k} + m_D w_D A_{f,k} \qquad [kg\ a^{-1}] \qquad (26)$$

where

m_D	*[kg m⁻²]*	is the biomass of deep burrowing fauna (travelling between the deep soil and the topsoil); and
w_D	*[a⁻¹]*	is the soil mass transferred from the deep soil to the topsoil per unit biomass of deep burrowing fauna (e.g. worms) per year.

The solid material flux from the bed sediments to the surface water due to resuspension, $M_{S,W}$, is given by the mass and turnover rate of the bed sediments:

$$M_{S,W} = \kappa_{SW} w_W l_W l_S (1 - \varepsilon_S) \rho_S \qquad [kg\ a^{-1}] \qquad (27)$$

where

κ_{SW}	*[a⁻¹]*	is the turnover rate of bed sediment to suspended solids in the water column of surface water; and
w_W	*[m]*	is the width of the surface water;
l_W	*[m]*	is the length of the surface water; and
l_S	*[m]*	is the vertical thickness of the bed sediment.

The remaining solid material transfers are determined on the basis of the solid material balances (see Fig. 4-6). The solid material flux between the topsoil and the deep soil, $M_{Tk,Dk}$, is given by:

$$M_{Tk,Dk} = M_{U,Tk} + M_{L,Tk} + M_{W,Tk} + M_{S,Tk} + M_{Dk,Tk} - M_{Tk,W} \qquad [kg\ a^{-1}] \qquad (28)$$

The solid material flux between the deep soil and the variably saturated zone, $M_{Dk,V}$, is given by:

$$M_{Dk,V} = M_{Tk,Dk} + M_{V,Dk} - M_{Dk,Tk} - M_{Dk,W} \qquad [kg\ a^{-1}] \qquad (29)$$

In cases where there is a net accumulation of solid material in the variably saturated zone, the balance is maintained through a transfer to elsewhere, $M_{V,E}$, and is given by:

$$M_{V,E} = M_{V,E}^{susp} + \max\left\{M_{U,V} + M_{S,V} - M_{V,E}^{susp} - M_{V,S} + M_{L,V} - M_{V,L} + \sum_k \left(M_{Dk,V} - M_{V,Dk}\right), 0\right\} \qquad [kg\ a^{-1}] \qquad (30)$$

In cases where there is a net loss of solid material from the variably saturated zone, the balance is maintained by drawing uncontaminated solid material from elsewhere (e.g. conceptually, from the hillsides adjacent to the valley). To avoid redefining $M_{U,V}$, the solid material balance is defined as, $M_{C,V}$, and is given by:

$$M_{C,V} = \max\left\{M_{V,S} + M_{V,E}^{susp} + M_{V,L} - M_{U,V} - M_{S,V} - M_{L,V} + \textstyle\sum_k\left(M_{V,Dk} - M_{Dk,V}\right), 0\right\} \quad [kg\ a^{-1}] \tag{31}$$

In cases where there is a net accumulation of solid material in the local aquifer, the balance is maintained through a transfer to elsewhere, $M_{L,E}$, and is given by:

$$M_{L,E} = M_{L,E}^{susp} + \max\left\{M_{U,L} + M_{S,L} - M_{L,E}^{susp} - M_{L,S} + M_{V,L} - M_{L,V} - \textstyle\sum_k\left(M_{L,Tk}\right), 0\right\} \quad [kg\ a^{-1}] \tag{32}$$

In cases where there is a net loss of solid material from the local aquifer, the balance is maintained by drawing uncontaminated solid material from the geosphere. To avoid redefining $M_{U,L}$, the solid material is taken from the contaminated geosphere (but without any associated contamination), $M_{C,L}$, and is given by:

$$M_{C,L} = \max\left\{M_{L,S} + M_{L,E}^{susp} - M_{U,L} - M_{S,L} + M_{L,V} - M_{V,L} + \textstyle\sum_k\left(M_{L,Tk}\right), 0\right\} \quad [kg\ a^{-1}] \tag{33}$$

The solid material flux between the surface water and bed sediment, $M_{W,S}$, is given by:

$$M_{W,S} = M_{S,W} + M_{S,L} + M_{S,V} + \textstyle\sum_k M_{S,Tk} - M_{L,S} - M_{V,S} \quad [kg\ a^{-1}] \tag{34}$$

The solid material flux from the surface water to elsewhere (e.g. due to flooding), $M_{W,E}$, is given by:

$$M_{W,E} = M_{U,W} + M_{S,W} - M_{W,S} + \textstyle\sum_k\left(M_{Tk,W} + M_{Dk,W} - M_{W,Tk}\right) \quad [kg\ a^{-1}] \tag{35}$$

4.2.3.4 Diffusive transfers

In the reference biosphere case, diffusive transfers operate between the topsoil and the deep soil, the deep soil and the variably saturated zone, the variably saturated zone and the local aquifer, and the local aquifer and the bed sediment (see Fig. 4-10).

In cases where the variably saturated zone is fully saturated and connected with the surface water body (e.g. the drained farmland case), diffusive transfers operate between the variably saturated zone and the bed sediment rather than between the local aquifer and the bed sediment. In cases where the variably saturated zone is frozen (colder climate), there is no diffusion to/from the variably saturated zone.

Nomenclature for diffusive transfers is described in Tab. 4-5.

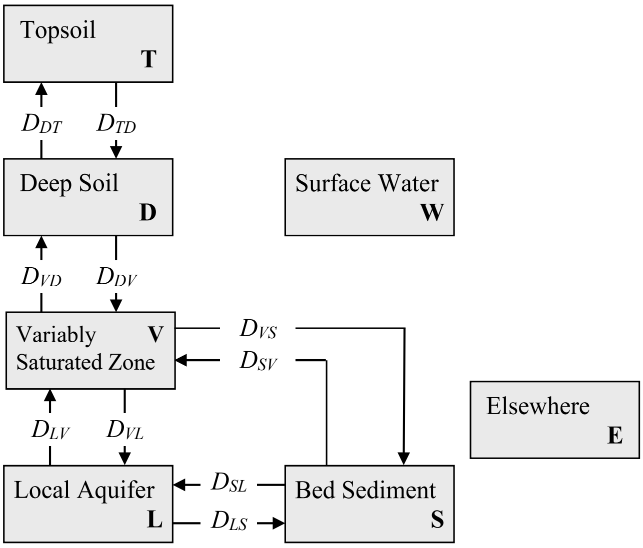

Fig. 4-10: Intercompartmental diffusive fluxes

Situation for a model with a single soil area.

Tab. 4-5: Nomenclature of diffusive transfers

Symbol	Description
$D_{L,V}$	Diffusive transfer from the local aquifer to the variably saturated zone
$D_{V,L}$	Diffusive transfer from the variably saturated zone to the local aquifer
$D_{V,Dk}$	Diffusive transfer from the variably saturated zone to the deep soil for soil area *k*
$D_{Dk,V}$	Diffusive transfer from deep soil to the variably saturated zone for soil area *k*
$D_{Dk,Tk}$	Diffusive transfer from deep soil to topsoil for area *k*
$D_{Tk,Dk}$	Diffusive transfer from topsoil to deep soil for area *k*
D_{LS}	Diffusive transfer from the local aquifer to the river bed sediment
D_{SL}	Diffusive transfer from the river bed sediment to the local aquifer
D_{VS}	Diffusive transfer from the variably saturated zone to the river bed sediment (applicable in the drained farmland case)
D_{SV}	Diffusive transfer from the river bed sediment to the variably saturated zone (applicable in the drained farmland case)

The effective diffusion rate for dissolved radionuclides from compartment *i* to compartment *j*, D_{ij}, is approximately given by (see also discussion in Appendix C of Klos et al. (1996)):

$$D_{ij} = s_{ij} \frac{1}{l_i \min\{l_i, l_j\}} \cdot \frac{D_0}{T_i} \quad [a^{-1}] \qquad (36)$$

where

s_{ij}	*[-]*	is an area scaling factor, equal to 1 except for the transfer from the variably saturated zone (V) to the deep soil (D), where it accounts for the differing sizes of the two compartments where multiple soil areas are represented;
l_i and l_j	[m]	are the length scales of the donor and receptor compartments in the direction of the diffusive exchange, respectively;
D_0	*[m^2 a^{-1}]*	is the ionic diffusion constant in pure water; and
T_i	*[-]*	is the compartmental tortuosity, the definition for which includes consideration of porosity.

The area scaling factor handles cases where the area of interface between the compartments does not cover the full area. This applies to the transfer from the variably saturated zone to the deep soil when multiple soil areas are used. In that case, the transfer rates for the separate deep soil compartments are scaled by the fraction of the overall area that they represent (BFE 2008).

4.2.3.5 Gas transfers

Some radionuclides can potentially be lost from the topsoil to the atmosphere via degassing. In most cases, potential losses via this route are conservatively ignored; however, degassing losses from soil can be notable for C-14, so a transfer process is included to explicitly represent this case. This is further discussed in Walke & Thorne (2023).

The gas loss transfer from the topsoil is represented as a specified transfer rate, λ_{TE}, to outside the biosphere system. This is illustrated conceptually in Fig. 4-7 as a transfer into the atmosphere. The transfer takes radionuclides out of the biosphere system via the atmosphere, which is re-presented in the model as a transfer to elsewhere. If the gas loss contributes to inhalation exposure, then the gas loss rate can also be used in the exposure model, see Section 4.2.4.9.

4.2.4 Representation of exposure pathways

The dynamic transport model provides time-dependent inventories of radionuclide *N* in compartment *i* as a function of time, $N_i(t)$. The annual individual effective dose from exposure to radionuclide *N* in all compartments *i* for exposure pathway *p*, $D_p^{(N)}(t)$, is given by:

$$D_p^{(N)}(t) = \sum_i H_{exp}^{(N)} E_p P_{p,i} N_i(t) \qquad [Sv\ a^{-1}] \quad (37)$$

where

$D_p^{(N)}$	*[Sv a^{-1}]*	is the annual individual effective dose from exposure to radionuclide *N* in each of the *i* compartments for exposure pathway *p*;
$H_{exp}^{(N)}$	*[Sv Bq^{-1}]*	is the dose per unit intake or exposure for radionuclide *N*;
E_p	*[E_p $P_{p,i}$] = a^{-1}*	is an exposure factor for the pathway, e.g. consumption rate or occupancy, and
$P_{p,i}$		is a processing factor that converts the inventory in compartment *i*, N_i, into a concentration;
N_i	*[Bq]*	is a time-dependent inventory of *N* in compartment *i*.

4.2.4.1 Compartmental concentrations

Volumetric concentrations for the compartments, C_i, are simply defined by the inventory divided by the physical compartment volume. For the local aquifer, the topsoil and surface water, the volumetric concentrations are therefore:

$$C_L \equiv \frac{N_L}{l_L A_f}, \quad C_{Tk} \equiv \frac{N_{Tk}}{l_T A_{f,k}}, \quad C_W \equiv \frac{N_W}{l_W w_W d_W} \qquad [Bq\ m^{-3}] \qquad (38)$$

where

N_i	*[Bq]*	is the amount in the local aquifer (L), topsoil area k (Tk) and surface water (W), respectively, as prescribed in Equation 1;
l_L and l_T	*[m]*	are the vertical thicknesses of the local aquifer and topsoil, respectively;
l_W	*[m]*	is the length of the surface water;
w_W	*[m]*	is the width of the surface water; and
d_W	*[m]*	is the depth of surface water.

The volumetric concentration includes the radionuclides in both solid state and solution. The concentrations in groundwater in the compartments can then be derived from these. For example, the concentration of the radionuclides in the well water, C_{well}, includes radionuclides both in solution and adsorbed onto suspended particles, and in the reference biosphere case it is approximately given by[8]:

$$C_{well} = \frac{1+(1-f_{filter})\alpha_L K_{d,L}}{\theta_L+(1-\varepsilon_L)\rho_L K_{d,L}} C_L \qquad [Bq\ m^{-3}] \qquad (39)$$

where

f_{filter}	*[-]*	is the fraction of suspended solid material removed by filtering before consumption.

When the variably saturated zone is saturated (e.g. in the drained farmland case), the well draws groundwater from both the aquifer and the variably saturated zone, and C_{well} reflects the average groundwater concentration across both compartments (weighted by the relative thickness of each layer).

4.2.4.2 Drinking water consumption

The effective dose from the consumption of water from the local aquifer, D_{well}, is given by:

$$D_{well} = f_{Local,wat} H_{ing} I_{wat} f_{well} C_{well} \qquad [Sv\ a^{-1}] \qquad (40)$$

where

$f_{Local,wat}$	*[-]*	is the fraction of food intake from the local biosphere area;
H_{ing}	*[Sv Bq^{-1}]*	is the effective dose per unit intake via ingestion;
I_{wat}	*[m^3 a^{-1}]*	is the total annual consumption of drinking water; and
f_{well}	*[-]*	is the fraction of drinking water obtained from the local aquifer.

[8] See Klos et al. (1996) for discussion of mathematical simplifications regarding environmental concentrations and the application of the Kd-concept.

The effective dose from the consumption of surface water, D_{wat}, is given by:

$$D_{wat} = f_{Local,wat} H_{ing} I_{wat} (1 - f_{well}) \frac{1+(1-f_{filter})\alpha_W K_{d,W}}{1+\alpha_W K_{d,W}} C_W \qquad [Sv\ a^{-1}] \qquad (41)$$

4.2.4.3 Fish consumption

The equilibrium concentration in fish tissue depends on the total volumetric concentration in the surface water without suspended sediment. The annual individual effective dose from consumption of fish, D_{ff}, is given by:

$$D_{ff} = f_{Local,fish} H_{ing} I_{ff} \frac{K_{ff}}{1+\alpha_W K_{d,W}} C_W \qquad [Sv\ a^{-1}] \qquad (42)$$

where

$f_{Local,fish}$	*[-]*	is the fraction of fish intake from the local biosphere area;
I_{ff}	*[kg a⁻¹]*	is the exposed individual's fish consumption rate expressed on a fresh-weight basis (defined below); and
K_{ff}	$[(Bq\ kg^{-1})\ (Bq\ m^{-3})^{-1}]$	is the concentration factor relating the concentration in the edible fish to the concentration in the surface water on a fresh-weight basis.

4.2.4.4 Crop consumption

The annual individual effective dose from consumption of crops, D_{crops}, is given by:

$$D_{crops} = \sum_{crops} f_{Local,crop} H_{ing} I_{crop} \left(C_{\substack{root \\ uptake}} + C_{\substack{irrigation \\ interception}} + f_{soil} C_{\substack{surface \\ contamination}} \right) \qquad [Sv\ a^{-1}] \qquad (43)$$

where

$f_{Local,crop}$	$[-]$	is the fraction of each crop obtained from the local area;
I_{crop}	$[kg\ a^{-1}]$	is the ingestion rate for each crop expressed on a fresh-weight basis;
$C_{\substack{root \\ uptake}}$	$[Bq\ kg^{-1}]$	is the concentration in crops arising from root uptake, on a fresh-weight basis;
$C_{\substack{irrigation \\ interception}}$	$[Bq\ kg^{-1}]$	is the concentration in crops arising from interception of irrigation water, on a fresh-weight basis;
f_{soil}	$[-]$	is the fraction of the external soil contamination that is retained on the edible part of the plant after food processing; and
$C_{\substack{surface \\ contamination}}$	$[Bq\ kg^{-1}]$	is the concentration in crops arising from soil contamination, on a fresh-weight basis.

The concentration in the crop comprises that taken up via the roots, that associated with intercepted irrigation water and that associated with soil (in the associated area) adhering to the edible crop. The concentration in the crop due to root uptake is given by:

$$C_{\substack{root\\uptake}} = K_{crop} \frac{C_{Tk}}{\rho_{Tk}(1-\varepsilon_{Tk})} \qquad [Bq\ kg^{-1}] \qquad (44)$$

where

K_{crop} $[(Bq\ kg^{-1})\ (Bq\ kg^{-1})^{-1}]$ is the transfer factor between the dry-weight soil and fresh-weight edible crop.

Note that C-14 represents a special case whereby degassing from the soil and uptake via stomata and photosynthesis can contribute to concentrations in plants. As a result, the value for K_{crop} for C-14 is calculated taking this into account, as described in Guillemot et al. (2024).

The concentration in the crop due to interception of irrigation water accounts for the fact that irrigation is not evenly distributed through the year. It will be applied during summer months, when the soil moisture deficit is at its greatest and as crops approach maturity. For this reason, interception fractions can be relatively high. The concentration is given by:

$$C_{\substack{irrigation\\interception}} = \left(1 - e^{-\mu_{crop}B_{crop}}\right)\left(\frac{f_{abs}f_{trans}f_{int}}{Y_{crop}} + \frac{(1-f_{abs})f_{ext}}{Y_{crop}W_{crop}(t_{irrig,1}-t_{irrig,2})}\left(e^{-W_{crop}t_{irrig,2}} - e^{-W_{crop}t_{irrig,1}}\right)\right) S_{irrigation} \qquad [Bq\ kg^{-1}] \qquad (45)$$

where

μ_{crop}	$[m^2\ kg^{-1}]$	is the interception factor for the crop;
B_{crop}	$[kg\ m^{-2}]$	is the above-ground dry-standing biomass at the time of irrigation;
f_{abs}	[-]	is the fraction of the intercepted contamination absorbed to the internal parts of the plant;
f_{trans}	[-]	is the fraction of absorbed contamination translocated into the edible parts of the plant;
f_{int}	[-]	is the fraction of the contamination in the internal edible parts of the plant that remain after food processing;
Y_{crop}	$[kg\ m^{-2}]$	is the fresh-weight yield of the crop;
f_{ext}	[-]	is the fraction of the external intercepted contamination that is retained on the edible parts of the plant after food processing;
W_{crop}	$[a^{-1}]$	is the weathering loss term from the external surfaces of the crop;
$t_{irrig,1}$	[a]	is the time between start of irrigation and harvest; and
$t_{irrig,2}$	[a]	is the time between end of irrigation and harvest.

and where $S_{irrigation}$ is the rate of radionuclides in irrigation water applied during the period of irrigation (Bq m^{-2}), defined as:

$$S_{irrigation} = \frac{1}{A_f}\left(\frac{\sum_k\left(Irri_{L,k}A_{f,k}\right) C_L}{\theta_L+(1-\epsilon_L)\rho_L K_{d,L}} + \sum_k\left(Irri_{W,k}A_{f,k}\right)\ C_W\right) \qquad [Bq\ kg^{-1}] \qquad (46)$$

The concentration in the crop due to surface contamination is given by (note that this assumes that the soil adhered to the edible crop is saturated):

$$C_{\substack{surface \\ contamination}} = S_{crop} \frac{C_{Tk}}{\rho_{Tk}(1-\varepsilon_{Tk})+\epsilon_{Tk}\rho_W} \qquad [Bq\ kg^{-1}] \qquad (47)$$

where

S_{crop}	*[kg kg⁻¹]*	is the soil contamination on the edible crop, based on saturated soil and fresh-weight crop.

4.2.4.5 Meat consumption

The annual individual effective dose from consumption of meat (beef and chicken), D_{meat}, is given by:

$$D_{meat} = \sum_{meat} f_{Local,meat} H_{ing} I_{meat} K_{meat} \left(I^{livestock}_{water} + I^{livestock}_{\substack{irrigation \\ interception}} + I^{livestock}_{\substack{root \\ uptake}} + I^{livestock}_{\substack{soil \\ contamination}} \right) \qquad (48)$$

$[Sv\ a^{-1}]$

where

$f_{Local,meat}$	*[-]*	is the fraction of each type of meat obtained from the local area
I_{meat}	$[kg\ a^{-1}]$	is the annual consumption of meat on a fresh-weight basis; and
K_{meat}	$[(Bq\ kg^{-1})\ (Bq\ d^{-1})^{-1}]$	is the transfer factor from animal ingestion to meat.

The animal's intake arising from its consumption of (unfiltered) water is given by:

$$I^{livestock}_{water} = I_{wc}\left(f_A \frac{1}{\theta_L + (1-\varepsilon_L)\rho_L K_{d,L}} C_L + (1-f_A) C_W \right) \qquad [Bq\ d^{-1}] \qquad (49)$$

where

I_{wc}	$[m^3\ d^{-1}]$	is the daily water consumption by the animal; and
f_A	*[-]*	is the fraction of the animal's water demand obtained from the well.

The animal's intake arising from the interception of irrigation water by pasture (cattle) or grain (chickens) is given by:

$$I^{livestock}_{\substack{irrigation \\ interception}} = \begin{cases} Z I_{pc} C_{\substack{irrigation \\ interception}} & \text{(pasture)} \\ I_{pc} C_{\substack{irrigation \\ interception}} & \text{(grain)} \end{cases} \qquad [Bq\ d^{-1}] \qquad (50)$$

where

Z	$[kg\ kg^{-1}]$	is the ratio by weight of fresh pasture to hay; and
I_{pc}	$[kg\ d^{-1}]$	is the daily consumption rate of fodder by the animal, on a dry-weight basis.

The animal's intake arising from root uptake by pasture or grain is given by:

$$I^{livestock}_{\substack{root\\uptake}} = \begin{cases} Z I_{pc} C^{pasture}_{\substack{root\\uptake}} & \text{(pasture)} \\ I_{pc} C^{grain}_{\substack{root\\uptake}} & \text{(grain)} \end{cases} \qquad [Bq\ d^{-1}] \qquad (51)$$

The animal's intake arising from soil contamination of pasture or grain is given by:

$$I^{livestock}_{\substack{soil\\contamination}} = \begin{cases} Z I_{pc} C^{pasture}_{\substack{surface\\contamination}} & \text{(pasture)} \\ I_{pc} C^{grain}_{\substack{surface\\contamination}} & \text{(grain)} \end{cases} \qquad [Bq\ d^{-1}] \qquad (52)$$

4.2.4.6 Milk consumption

The annual individual effective dose from the consumption of milk is given by:

$$D_{milk} = f_{Local,milk} H_{ing} I_{milk} K_{milk} \left(I^{livestock}_{water} + I^{livestock}_{\substack{pasture\\interception}} + I^{livestock}_{\substack{pasture\ root\\uptake}} + I^{livestock}_{\substack{soil\\contamination}} \right) [Sv\ a^{-1}] \qquad (53)$$

where

$f_{Local,milk}$	*[-]*	is the fraction of milk obtained from the local area;
I_{milk}	*[kg a^-1]*	is the annual consumption of milk; and
K_{milk}	*[(Bq kg^-1) (Bq d^-1)^-1]*	is the transfer factor from animal ingestion to milk.

4.2.4.7 Egg consumption

The annual individual effective dose from the consumption of eggs is given by:

$$D_{eggs} = f_{Local,eggs} H_{ing} I_{eggs} K_{eggs} \left(I^{poultry}_{water} + I^{poultry}_{\substack{pasture\\interception}} + I^{poultry}_{\substack{pasture\ root\\uptake}} + I^{poultry}_{\substack{soil\\contamination}} \right) [Sv\ a^{-1}] \qquad (54)$$

where

$f_{Local,eggs}$	*[-]*	is the fraction of eggs obtained from the local area;
I_{eggs}	*[kg a^-1]*	is the annual consumption of eggs; and
K_{eggs}	*[(Bq kg^-1) (Bq d^-1)^-1]*	is the transfer factor from animal ingestion to eggs.

4.2.4.8 External irradiation

The annual individual effective dose is given by:

$$D_{ext} = G \sum_k C_{Tk} f_{Local,soil,k} \qquad [Sv\ a^{-1}] \qquad (55)$$

where

G $[(Sv\ a^{-1})\ (Bq\ m^{-3})^{-1}]$ is the effective dose coefficient due to external irradiation; and

$f_{Local,soil}$ $[-]$ is the occupancy fraction of each soil area.

The dose coefficient, G, takes into account the individual occupancy of the contaminated area, which is taken to be continuous (i.e. one year per year), but can be scaled by the local fraction $f_{Local,soil}$. The average concentration over the various soil areas is used, weighted by the occupancy of each area.

4.2.4.9 Inhalation

Radionuclides can be inhaled either in their gaseous form following degassing from the soil or in the form of suspended soil particles that have concentrations determined by the sorption on the topsoil. The dose from inhalation, D_{inh}, is therefore given by:

$$D_{inh} = D_{dust} + D_{gas} \qquad [Sv\ a^{-1}] \quad (56)$$

where the contribution from inhalation of dust, D_{dust}, is given by:

$$D_{dust} = H_{dust} I_{air} \sum_k \left(\frac{O_f a_f + (1 - O_f) a_r}{(1 - \varepsilon_{Tk}) \rho_{Tk}} \right) C_{Tk} f_{Local,soil,k} \qquad [Sv\ a^{-1}] \quad (57)$$

where

H_{dust} $[Sv\ Bq^{-1}]$ is the effective dose per unit intake via inhalation of dust (particulates);

I_{air} $[m^3\ a^{-1}]$ is the annual volume of air inhaled by the exposed individual;

O_f $[-]$ is the fractional annual occupancy at the occupational/elevated dust concentration;

a_f $[kg\ m^{-3}]$ is the occupational/elevated dust concentration; and

a_r $[kg\ m^{-3}]$ is the background dust concentration.

and where the contribution from inhalation of gas, D_{gas}, is given by:

$$D_{gas} = H_{gas} I_{air} \sum_k \left(\lambda_{dg} \frac{l_{Tk} l_W}{v_A l_A} \right) C_{Tk}\, f_{Local,soil,k} \qquad [Sv\ a^{-1}] \quad (58)$$

where

H_{gas} $[Sv\ Bq^{-1}]$ is the effective dose per unit intake via inhalation of gas;

λ_{dg} $[a^{-1}]$ is the volatile element degassing rate;

l_{Tk} $[m]$ is the thickness of the topsoil for soil area k;

l_W $[m]$ is the length of the surface water, which represents the length of the valley section;

l_A $[m]$ is the thickness of the atmosphere affected by degassing and associated with inhalation; and

v_A $[m\ a^{-1}]$ is the mean annual wind velocity.

Again, the average concentration over the various soil areas is used, weighted by the occupancy of each area.

4.2.5 Exposure factors for food consumption

The exposure factors are defined to consistently represent the habits and behaviour of an individual member of the modelled community. Each of the ingestion rates of a particular foodstuff, I_f, in the exposure model is defined in terms of their fractional contribution to the total annual energy intake from food consumption:

$$I_f = \frac{E_0 f_f}{\eta_f} \qquad [kg\ a^{-1}] \qquad (59)$$

where

E_0	$[kJ\ a^{-1}]$	is the total annual energy intake from food;
f_f	[-]	is the fraction of the total food energy from each foodstuff; and
η_f	$[kJ\ kg^{-1}]$	is the energy content of the foodstuff.

In the reference biosphere case, the exposure factors represent a largely closed, self-sufficient agricultural community. All foodstuffs in the modelled region are therefore considered to be produced locally as far as practicable so that the dose calculated is not reduced by the consumption of uncontaminated foodstuffs. A local fraction can be specified for each foodstuff to represent the case where some of the food intake is obtained from uncontaminated foodstuffs outside of the biosphere area, such as in the case of ingestion of fish.

The consumption rate of drinking water takes account of the consumption rate of milk and is defined as:

$$I_{wat} = I_{fluid} - I_{milk} \qquad [m^3\ a^{-1}] \qquad (60)$$

where

I_{fluid}	$[m^3\ a^{-1}]$	is the exposed individual's total annual fluid consumption via drinking water and milk.

4.3 Calculation cases, assumptions and dealing with uncertainties

Uncertainty about the nature of the biosphere that might receive potentially contaminated groundwater over long timescales, the behaviour of radionuclides within the biosphere, and about the range and representation of different exposure pathways is unavoidable. As described in Chapter 2, the aim of the biosphere modelling is to demonstrate that the repository system is sufficiently protective of humans and the environment in the long term. Biosphere modelling provides a tool for evaluating the potential radiological significance of radionuclide releases in groundwater.

Present-day conditions provide the basis for the reference biosphere case because temperate, interglacial conditions allow for maximum use of the local environment. Use of present-day conditions also gives confidence that the biosphere modelling is plausible and internally consistent because the situations observed today provide an analogue of conditions that can be expected to arise in the future.

Uncertainties about the nature of the biosphere in the distant future are explored through alternative cases that sit alongside the reference biosphere case. These are identified in Section 3.1 by considering how external factors will shape the biosphere in the long term, principally through climate, geomorphological processes, regional-scale hydrogeology and human behaviour. The alternative cases represent:

- a case with a warmer-drier climate that provides a reasonable upper bound in terms of potential for exploitation of shallow groundwater and for lower hydrologically effective rainfall (resulting in a lower potential for dilution of releases to the biosphere);
- a case with a colder climate that provides a reasonable lower bound for conditions in which humans can remain present in the landscape. This case features more limited pathways to the surface (because of the presence of permafrost) and lower productivity, requiring larger resource areas and the import of food to sustain the population; and
- a case where the water table is closer to the soil surface that reflects an alternative geomorphological context, allowing different characteristics and pathways to be considered (e.g. potential for flooding).

In addition to evaluating the radiological significance of potential contaminant releases to the surface, biosphere modelling also provides a tool for identifying important processes and pathways. Specific conceptual uncertainties are explored in Section 6.3 through deterministic sensitivity calculations. These explore the degree of pessimism in the self-sufficient lifestyle assumptions, the effect of the size of the valley section and coupled flow rates (i.e. smaller valley with lower flow rates and larger valley with higher flow rates), and the effect of radionuclide discharging directly into surface water (as opposed to release into the local aquifer). Section 6.3 describes how probabilistic calculations are also used to explore the sensitivity of the biosphere modelling to parameter variations not investigated through the alternative biosphere cases or deterministic sensitivity cases.

5 Data, assumptions and uncertainties

The context, calculation cases and the conceptual and mathematical models for representing the biosphere in post-closure assessments for the RBG application are presented in the preceding chapters. This chapter presents and justifies the data needed to populate the mathematical model.

Data relating to biosphere characteristics (i.e. those that principally distinguish the different biosphere calculation cases) are presented in Section 5.1. Exposure group data are presented in Section 5.2. Element-independent data relating to crops and animal produce are presented in Section 5.3. Element-dependent biosphere data are then presented in Section 5.4 and radionuclide-dependent data are presented in Section 5.5.

There is inherent uncertainty associated with the data. Section 2.3 notes that the biosphere modelling aims to build confidence that the potential significance of any radionuclide releases to the biosphere is not underestimated while simultaneously avoiding an overly pessimistic assessment. This is achieved through being realistic in modelling radionuclide behaviour in the biosphere, while erring on the side of pessimism in representing potential exposure pathways. In this way, parameter values for characterising the biosphere and representing radionuclide migration aim to be best estimates.

Given the complexity of the system and the long timescales involved, a deterministic approach is adopted, with sensitivity of the results to parameter uncertainty explored through alternative calculation cases, and through deterministic and probabilistic sensitivity analyses. Deterministic parameter values are given in the following sections, and the ranges used for sensitivity calculations are presented in Section 6.3.

Radionuclides in groundwater are not expected to reach the surface environment for a very long time after closure, i.e. timescales of tens to hundreds of thousands of years. Should radionuclides reach the surface, those releases would occur over extended periods of time, i.e. timescales of hundreds to thousands of years. Therefore, the biosphere modelling seeks to represent long-term behaviour and long-term averages that are appropriate in terms of parameter values. Characteristics of the different components within the biosphere are assumed to be relatively homogenous and adequately represented by spatially averaged properties.

5.1 Data relating to biosphere characteristics

Characteristics of the reference biosphere case have been reasonably consistent through previous assessment iterations (Nagra 2014, Nagra 2010, Brennwald & van Dorp 2008, Nagra 2002b, Klos et al. 1996). They have been subject to on-going review, including reviews of aquifer properties (Appendix 1 of Nagra (2010)), irrigation habits and rates (Appendix A of Nagra (2014)), conditions for warmer-drier climates (Appendix B of Nagra (2014)), and a detailed review of the characteristics of present-day locations in Northern Switzerland (Haldimann & Schatzmann (2014) in support of Nagra (2014)). The parameters defining the reference biosphere and for the warmer-drier climate case have been reviewed again in preparation for the RBG and continue to provide a suitable basis for assessment. The parameter values and supporting arguments are presented below, including minor refinements.

Defining characteristics for the reference biosphere and warmer-drier climate cases are presented in Section 5.1.1. Modifications compared to the reference biosphere case for the cold climate and drained farmland cases are then presented in Section 5.1.2.

5.1.1 Characteristics for the reference biosphere and warmer-drier climate cases

Compartment-independent characteristics for the reference biosphere and warmer-drier cases are given in Tab. 5-1; compartment-dependent characteristics are given in Tab. 5-2. Supporting arguments are provided below each table, drawing on previous justifications and more recent review.

Tab. 5-1: Compartment-independent characteristics for the reference biosphere and warmer-drier climate calculation cases

Footnotes discussing parameter values are included below the table.

Symbol	Units	Description	Value		Note
			Reference	Warmer-drier	
A_f	m^2	Surface area of the biosphere region	2.275E+6		1
D_0	$m^2\ a^{-1}$	Ionic diffusion constant in pure water	0.038		2
d_{ETP}	$m\ a^{-1}$	Mean annual evapotranspiration rate	0.6	0.6	3
d_{PPT}	$m\ a^{-1}$	Mean annual precipitation rate	1	0.3	4
d_{RO}	$m\ a^{-1}$	Mean annual surface runoff (overland flow)	0		5
d_{capil}	$m\ a^{-1}$	Mean annual rate of capillary rise	0		6
$Irri_L$	$m\ a^{-1}$	Mean annual rate of irrigation with groundwater from the local aquifer	0.3	0.6	7
$Irri_W$	$m\ a^{-1}$	Mean annual rate of irrigation with surface water (including flooding)	0		8
F_{CL}	$m^3\ a^{-1}$	Flux of contaminated deep groundwater into local aquifer	1.3E+5		9
F_{CW}	$m^3\ a^{-1}$	Flux of contaminated deep groundwater into surface water	0		10
F_{UL}	$m^3\ a^{-1}$	Flux of uncontaminated water into local aquifer	1.48E+6	1.1E+6	11
F_{UW}	$m^3\ a^{-1}$	Flux of uncontaminated water into surface water	1.17E+10	4.0E+9	12
Rel_L	-	Fraction of release into local aquifer	1		13
Rel_W	-	Fraction of release into surface water	0		13
m_e	$kg\ m^{-2}\ a^{-1}$	Erosion	0.27		14
m_{SL}	$kg\ m^{-2}\ a^{-1}$	Annual transfer from bed sediment to agricultural land	0		15

Symbol	Units	Description	Value		Note
		(per unit area of land, not bed, sediment)			
m_{dep}	kg m^{-2} a^{-1}	Sedimentation onto topsoil	0		16
κ_S	a^{-1}	Turnover rate: bed sediment to suspended solid in water column	1		17
w_D	a^{-1}	The frequency with which the body mass carried by a single worm is transferred to the topsoil per year	20		18
m_D	kg m^{-2}	Biomass of deep burrowing fauna (travelling between the deep soil and the topsoil)	0.1		18
v_A	m a^{-1}	Mean annual wind velocity	4.1E+7		19
l_A	m	Thickness of the atmosphere affected by degassing and associated with inhalation	2		20
d_W	m	Depth of surface water	3.25	1.3	21
w_W	m	Width of surface water	100		22

Notes for Tab. 5-1:

1 Based on characteristic sections of the Rhine below the Rhine Falls.

2 Based on measured values for colloidal environments (Cremers 1968).

3 Reference value represents typical actual evapotranspiration rate for the present-day climate in Northern Switzerland, consistent with previous assessments, and with recent climate data (e.g. Trabucco & Zomer (2019)). The value for a warmer-drier climate is based on reviews in Nagra (2010) and Nagra (2014); these adopted the same value as the reference biosphere case because the degree of actual evapotranspiration is inhibited by the lower amount of precipitation in the warmer-drier climate conditions.

4 The reference value represents the typical precipitation rate for the present-day climate in Northern Switzerland, consistent with previous assessments (Nagra 2010, Nagra 2014) and with recent climate data, including data from Fick & Hijmans (2017). The reference value is below the mean annual precipitation rate in Switzerland of 1458 mm a^{-1} as reported by Schädler & Weingartner (2002) because rainfall in Northern Switzerland is lower compared to the Alps in the south that typically has higher annual precipitation rates.

The value for the warmer-drier climate is representative of a more Mediterranean context. It is consistent with previous reviews (e.g. Appendix 2 in Nagra (2010)), bearing in mind that a warmer-drier climate is represented, as opposed to warm-humid conditions.

5 For both reference and warmer-drier conditions, hydrologically effective rainfall (HER, precipitation minus evapotranspiration) is assumed to infiltrate and not contribute to surface runoff.

6 Capillary rise captures any mechanism for vertical movement of radionuclides with water flows and includes fluctuations in the water table and episodic saturation as well as capillary suction. The notable distance (>5 m) between the topsoil and the water table means that both fluctuations in water table depth and capillary suction will be insufficient to draw water up through the sediment column. In these instances, capillary rise is set to zero.

With regard to the capillary rise component, the process is inversely related to effective pore diameter, which in turn is governed by grain size and grain-size distribution (i.e. texture) in a sediment or porous weathered bedrock. In a well-drained agricultural sandy mineral soil, the capillary rise would only be a few centimetres (Healy & Scanlon 2010).

7 Irrigation is considered to be drawn from the local aquifer rather than from surface water for the reference and warmer-drier climate cases. This is pessimistic, given that radionuclides discharge into the local aquifer, but not unreasonable, given the greater reliability and higher water quality of groundwater resources.

An irrigation rate of 0.3 m a^{-1} is used for the reference biosphere case, representing a suitable average value across the range of crop types; this is supported in Nagra (2010) with reference to average rates of irrigation reported under relatively dry conditions in Weber & Schild (2007) and further supported by the review in Appendix A of Nagra (2014).

The irrigation rate for warmer-drier conditions is based on the review in Appendix 2 of Nagra (2010) and supported by a further review in Appendix A of Nagra (2014). For context, the irrigation rate of 0.6 m a^{-1} corresponds to a several hours long watering rate of 5 mm h^{-1} over 30 days during the driest time of the year.

8 As noted above, irrigation is drawn from the local aquifer for the reference and warmer-drier climate cases, so the irrigation rate from surface water is set to zero.

9 The volumetric flow rate of groundwater discharging from depth to the local shallow aquifer is a challenging parameter to define; however, shallow groundwater flows will be dominated by shallow hydrogeology, such that the contribution of deep groundwater to shallow groundwater flow rates would be low. In previous assessments, the value has been based on (i) consideration of hydraulic conductivity and the hydraulic gradient of the groundwater pathway from depth (e.g. based on the Malm aquifer), and the potential cross-sectional area of the hypothetical "plume"; and (ii) review of the resulting flow rate against the overall groundwater flow rate through the shallow local aquifer. These considerations led to a flow rate of 1.3E+5 m^3 a^{-1}, discharging from depth into the local shallow aquifer[9], which represents about 10% of the overall flow through the local shallow aquifer. This value is retained for the reference and warmer-drier climate cases and is consistent with previous assessments (Nagra 2010, Nagra 2014).

10 The conceptual model for the reference biosphere is based on deep groundwater discharging to the local shallow aquifer, so the flow rate to the river is set to zero. The potential for direct groundwater discharge to surface water is explored in a sensitivity case in Section 6.3.1.

11 The reference value is based on consideration of (i) inflow from an upstream section of the gravel aquifer[10], and (ii) lateral inflow from the sides of the valley[11]; these considerations led to a value of 1.48E+6 m^3 a^{-1}, which was used in previous assessments (Nagra 2010, Nagra 2014). A review against the characteristics of a wide range of local aquifer characteristics in Haldimann & Schatzmann (2014) demonstrates that this is a reasonable and representative value.

The value for the warmer-drier climate is reduced in comparison to the reference biosphere case, which is consistent with previous assessments (Nagra 2010, Nagra 2014).

12 The reference value is based on the mean discharge in the Rhine river at the Rhine Falls (gauging site Rhein – Neuhausen), with reference to BWG (2001) and Schädler & Weingartner (1992); the reference value remained.

The reduction in river flow rate for warmer-drier conditions reflects the lower precipitation rate.

13 Consistent with F_{CL} and F_{CW}.

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[9] Based on characteristics of the Malm aquifer from Nagra (2002a), which supported a hydraulic conductivity of 5E-7 m s^{-1}, a hydraulic gradient of 0.05, and a cross-sectional area of 1.68E5 m^2. The hydraulic conductivity is relatively low, and it should be noted that this is taken to be characteristic of the pathway from depth.

[10] A hydraulic conductivity of 0.002 m s^{-1}, a hydraulic gradient of 0.0014, and a cross-sectional area of 1.3E5 m^2 deliver a flow rate of 1.15E+6 m a^{-1} from the upstream section.

[11] The hill slope contribution is taken to be 3.3e+5 m^3 a^{-1}; for context, an estimated hill slope area of 3.5E6 m^2 and a hillslope recharge rate of 0.1 m a^{-1} would deliver a flow rate from the valley sides of 3.5E+6 m^3 a^{-1}, so the value of 3.3E+5 is consistent and a little pessimistic in comparison.

14 The erosion rate from topsoil is based on consideration of compensating the overall rate of uplift. An uplift rate of 0.1 mm a^{-1} (based on Müller et al. (2002) and a dry bulk rock density of 2700 kg m^{-3} imply an erosion rate of 0.27 kg m^{-2} a^{-1}. This argument is relevant for both the reference and warmer-drier cases. The value is also consistent with soil erosion rates in agricultural settings in Montgomery (2007).

15 For the reference and warmer-drier climate cases, there is neither flooding nor dredging, and therefore, no transfer of river bed sediments to the topsoil.

16 The reference and warmer-drier climate cases do not include significant influx of uncontaminated sediment beyond that carried with the water flux.

17 Close to complete turnover of bed sediments over the course of a year is assumed, which is consistent with previous assessments (Nagra 2010, Nagra 2014).

18 Müller-Lemans & van Dorp (1996) identify a typical transfer rate for dry soil from deep soil to topsoil of 2 kg m^{-2} a^{-1}. The mass of earthworms (m_D) and the turnover rate (w_D) are calibrated to deliver this value by assuming m_D of 0.1 kg m^{-2} and a turnover rate equivalent to twenty times the earthworm mass in a year.

19 The typical long-term average wind speed is taken to be 1.3 m s^{-1} in Northern Switzerland, which equates to 4.1E+7 m a^{-1} (preserved from Brennwald & van Dorp (2008)).

20 A value of 2 m is taken as a pessimistic assumption as outdoor atmospheric mixing heights would typically be substantially larger.

21 The reference case represents a typical value for average water depth in a large Swiss river (e.g. the Rhine river below the Rhine Falls). The value for warmer-drier climate conditions is reduced, reflecting reduced inflow.

22 Typical value for a large river in Switzerland (e.g. width of the river below the Rhine Falls).

Tab. 5-2: Compartment-dependent characteristics for the reference biosphere and warmer-drier calculation cases

Footnotes discussing parameter values are included below the table.

Symbol	Units	Description	Compartment	Value		Note
				Reference	Warmer-drier	
l_i	m	Thickness of compartment/length of surface water	Topsoil (T)	0.25		1
			Deep soil (D)	2		2
			Var. sat. zone (V)	5		3
			Local aquifer (L)	20		4
			Bed sediment (S)	0.1		5
l_W	m	Length	Surface water (W)	3500		6
d_W	m	Depth	Surface water (W)	3.25	1.3	7
w_W	m	Width	Surface water (W)	100		8

Symbol	Units	Description	Compartment	Value		Note
				Reference	Warmer-drier	
ε_i	-	Total porosity	Topsoil (T)	0.4		9
			Deep soil (D)	0.4		9
			Var. sat. zone (V)	0.2		10
			Local aquifer (L)	0.2		10
			Surface water (W)	[calculated]		11
			Bed sediment (S)	0.5		12
θ_i	-	Volumetric moisture content	Topsoil (T)	0.3		13
			Deep soil (D)	0.3		13
			Var. sat. zone (V)	0.15		14
			Local aquifer (L)	0.2		15
			Surface water (W)	[calculated]		11
			Bed sediment (S)	0.5		16
ρ_i	kg m^{-3}	Solid (grain) density of compartment material	Topsoil (T)	2650		17
			Var. sat. zone (V)	2650		17
			Deep soil (D)	2650		17
			Local aquifer (L)	2650		17
			Bed sediment (S)	2650		17
ρ_W	kg m^{-3}	Density of water	Surface water (W)	1000		18
α_i	kg m^{-3}	Suspended solid concentration in water/porewater	Topsoil (T)	0.001		19
			Deep soil (D)	0.001		19
			Var. sat. zone (V)	0.001		19
			Local aquifer (L)	0.001		19
			Surface water (W)	0.1	0.3	20
			Bed sediment (S)	0.001		19
T_i	-	Tortuosity of compartment material	Topsoil (T)	3.9		21
			Deep soil (D)	3.9		21
			Var. sat. zone (V)	8.6		21
			Local aquifer (L)	8.6		21
			Surface water (W)	[not applicable]		-
			Bed sediment (S)	2.9		21

Notes for Tab. 5-2:

1 Typical value for thickness of topsoil; the depth covers the larger part of the roots and the typical depth of mixing through ploughing.

2 Considered the typical thickness of weathered material overlying the unconsolidated Quaternary sediments yet below the main rooting depth of soil.

3 Based on review of data from the Federal Office for the Environment (FOEN) national groundwater monitoring network (NAQUA) for depth to the water table in Swiss valleys where the distance to the river is consistent with the reference biosphere assumptions. This takes into account the thickness of the topsoil and of the deep soil; the approach is similar to the analysis presented in Collenteur et al. (2023).

4 Typical value for thickness of gravel aquifers in the regions considered in Northern Switzerland, based on groundwater maps (GWK (ZH) Blatt Diessenhofen, GWK (AG), Blatt Zurzach) and hydrogeological literature (Jäckli & Kempf 1972) and consistent with the average thickness of aquifers reviewed in Haldimann & Schatzmann (2014).

5 Assumed thickness of bed sediment layer. Usually, there is no clear distinction between this layer and the layers below. The considered sediment layer represents the part that is most affected by solid material turnover.

6 Typical stretch of valley in the region considered (i.e. Rhine valley below the Rhine Falls).

7 Consistent with previous assessments (Nagra 2010, Nagra 2014), a reference value of 3.25 m is taken to be characteristic of a larger river in Northern Switzerland; this is typical for the Rhine Falls Channel and within the range of characteristic depths reviewed in Haldimann & Schatzmann (2014).

The value for the warmer-drier climate case is scaled by the lower flow rate of the river, which is again consistent with previous assessments (Nagra 2010, Nagra 2014).

8 Consistent with previous assessments (Nagra 2010, Nagra 2014), based on the width of the Rhine in a section below Rhine Falls.

9 Typical value for soil porosity, representative of a more sandy mineral agriciltural soil, used for topsoil and deep soil, see Schachtschabel et al. (1989) and Carsel & Parrish (1988).

10 A low value is conservative because it minimises the volume of water into which radionuclides are released, so a low value is used compared to the porosity range in gravel aquifers (see Freeze & Cherry (1979)) for the local aquifer and for the variably saturated zone, which comprise the same material.

11 Calculated for this compartment according to: $\varepsilon_W = \theta_W = 1 - \frac{\alpha_W}{\rho}$, where ε_W is the total porosity, θ_W is the water-filled porosity, α_W is the suspended sediment concentration and ρ is the dry grain density of the sediment.

12 Larger porosity than for soil material, because process of compaction is less advanced.

13 Typical value for volumetric moisture content in soil. Note that the volumetric moisture content is smaller than the porosity, implying a saturation degree of 75%. This value is consistent with data for Northern Switzerland from the Swiss Soil Monitoring Network (NABO), as summarised in Metcalfe et al. (2023), which show volumetric water content of about 30% until reaching the wilting point for soils.

14 Taken to have 75% saturation, the same as the deep soil.

15 The local aquifer is fully saturated, so the water-filled porosity is equal to the total porosity.

16 Similarly, the river bed sediment is fully saturated, so the water-filled porosity is equal to the total porosity.

17 Typical value for solid density of soil material and consistent with the grain density of quartz given in Freeze & Cherry (1979). This value is used for the topsoil, deep soil, variably saturated zone and local aquifer. Its application to e.g. mineral soils is consistent with Schachtschabel et al. (1989) and Hillel (1980).

18 Density of water.

19 Typical value for suspended solid concentration in groundwater, see Vilks et al. (1993), McCarthy (2018). This value is taken to apply throughout the local aquifer, variably saturated zone, deep soil, topsoil and to river bed sediment.

In modelling, the value for river bed sediment can be applied to suspended sediment carried in recharge from the river to the local aquifer; in this context the suspended sediment concentration in groundwater is more applicable compared to the suspended sediment concentration in surface water because the recharging water will have been filtered through the river bed sediments.

20 Reference value represents a typical average value for the suspended solid concentration of rivers in Northern Switzerland, according to the data of Jakob & Spreafico (1997).

The warmer-drier climate case has the same erosion rate for soil, whereas the flow rate in the river is approximately three times lower compared to the reference biosphere case (see Tab. 5-1); this implies that the suspended sediment concentration in the river would be approximately three times higher. Therefore, a value of 0.3 kg m^{-3} is adopted.

21 Consistent with the original TAME models, tortuosity is derived from the total porosity by Burger's equation from Cremers et al. (1966), as discussed in Appendix C of Klos et al. (1996).

5.1.2 Characteristics for the cold climate and drained farmland cases

The conceptualisations for the cold climate and drained farmland cases differ sufficiently in structure from the reference biosphere case to justify the separate presentation of parameter sets for these cases below, along with the supporting discussion. Where parameter values are identical to those in the reference biosphere case, the parameter is omitted from the tables, unless the assumption merits some discussion.

The parameter values used for the cold climate case are given in Tab. 5-3 and those for the drained farmland case are given in Tab. 5-4.

Note that sorption coefficients, release rates of gas from the topsoil and human habits are also modified for these cases; the parameter values are given in Sections 5.3 and 5.4.

Tab. 5-3: Biosphere characteristics for the cold climate case

Footnotes discussing parameter values are included below the table.

Symbol	Units	Description		Value	Note
A_f	m^2	Surface area of the biosphere region		2.275E+6	1
$A_{f[crops]}$	m^2	Subarea of soil used for horticulture		1.6E+4	2
$A_{f[herding]}$	m^2	Subarea of soil used for herding and wild food		2.259E+6	3
d_{PPT}	m a^{-1}	Mean annual precipitation rate		0.7	4
d_{ETP}	m a^{-1}	Mean annual evapotranspiration rate		0.2	5
d_{RO}	m a^{-1}	Mean annual rate of surface runoff (overland flow)		0.2	6
d_{capil}	m a^{-1}	Mean annual rate of capillary rise		0.1	7
$Irri_L$	m a^{-1}	Mean annual rate of irrigation with groundwater from the local aquifer		0	8
$Irri_W$	m a^{-1}	Mean annual rate of irrigation with surface water (including flooding)	Crop area	0.1	9
			Herding area	0	10
F_{CL}	m^3 a^{-1}	Flux of contaminated deep groundwater into local aquifer		1.3E5	11
F_{CW}	m^3 a^{-1}	Flux of contaminated deep groundwater into surface water		0	12

Symbol	Units	Description			Value	Note
F_{UL}	$m^3\ a^{-1}$	Flux of uncontaminated water into local aquifer			1.85E6	13
F_{UW}	$m^3\ a^{-1}$	Flux of uncontaminated water into surface water			1.46E+10	13
Rel_L	-	Fraction of release into local aquifer			1	12
Rel_W	-	Fraction of release into surface water			0	12
m_e	$kg\ m^{-2}\ a^{-1}$	Erosion			0.34	14
w_D	a^{-1}	The frequency with which the body mass carried by a single worm is transferred to the topsoil per year			5	15
m_D	$kg\ m^{-2}$	Biomass of deep burrowing fauna (travelling between the deep soil and the topsoil)			0.05	15
ε_i	-	Total porosity	Topsoil (T)	Crop area	0.4	16
				Herding area	0.3	17
			Deep soil (D)		0.3	18
θ_i	-	Volumetric moisture content	Topsoil (T)	Crop area	0.3	19
				Herding area	0.225	19
			Deep soil (D)		0.25	19
			Permafrost layer (V)		0.2	20
l_i	m	Thickness of compartment	Topsoil (T)	Crop area	0.25	21
				Herding area	0.1	22
			Deep soil (D)	Crop area	0.75	23
				Herding area	0.9	23
ρ_i	$kg\ m^{-3}$	Solid (grain) density of topsoil (T)			2000	24
T_i	-	Tortuosity of compartment material	Topsoil (T)	Crop area	3.9	25
				Herding area	5.4	25
			Deep soil (D)		5.4	25
			Permafrost layer (V)		-	26

Notes for Tab. 5-3:

1 The same valley as in the reference biosphere case, so the overall area is the same (defined based on the area of the shallow local aquifer).

2 Equivalent to about 4 acres (around 1.6 ha), based on present-day examples of cultivation in Canadian tundra regions.

3 Area of biosphere region minus the small cultivated area.

4 Based on analogue climate stations from BIOCLIM (2004) and consistent with Walke et al. (2013b); note that water shed from polytunnels/greenhouses over the cultivated area is assumed to be collected and used to water crops grown under cover. The value is also consistent with case studies included in Lemieux et al. (2020).

5 Based on consideration of the precipitation value and climate, and consistent with Walke et al. (2013b).

6 Runoff will occur during snowmelt; adopted as a reasonable estimate.

7 No vertical movement of groundwater through the permafrost layer, but there is some capillary rise/advective movement with fluctuating groundwater level between the topsoil and deep soil compared to the reference biosphere case due to a more shallow groundwater table.

8 Surface water is plentiful and easily available in summer months, so no need for direct use of groundwater below the permafrost.

9 A small degree of irrigation is taken to be required during the short peak growing period for the area used for small-scale horticulture.

10 No irrigation of the wider area used for herding and there's taken to be no flooding of the grazed area from the river.

11 The groundwater discharge rate from depth is taken to be identical to that for the reference biosphere case; the value represents only a small contribution to the overall groundwater flow rate through the local aquifer, and is thus considered relatively unimportant.

12 As for the reference biosphere case, the potentially contaminated groundwater is taken to discharge to the local aquifer.

13 Scaled from the values used for the reference biosphere case by hydrologically effective rainfall (HER, precipitation minus evapotranspiration).

14 Taken to be 25% higher due to lack of vegetation cover and snow melt.

15 The soil biota transfer rate and the mass of soil biota combine to define mixing through bioturbation; this is taken to be very low for the cold climate case because the ground is mostly frozen and temperatures are low. However, this is partly compensated by cryoturbation.

16 Value for the cultivated area is assumed to be the same as in the reference biosphere case.

17 Value for wider soil area is taken to be lower, reflecting poorer soil compared to the reference biosphere case.

18 Reduced compared to the reference biosphere case to reflect less-developed soil profile due to cold climate conditions.

19 The degree of saturation is taken to be identical to that for the reference biosphere case; the water-filled porosity for the non-cultivated topsoil and the deep soil are, therefore, adjusted to reflect lower total porosity. These layers form the active layer and are seasonally frozen.

20 The permafrost layer is taken to be fully saturated and permanently frozen.

21 The thickness of the cultivated topsoil is assumed to be the same as in the reference biosphere case.

22 The uncultivated topsoil is taken to be thinner than the reference biosphere case.

23 The combined thicknesses of the topsoil and deep soil are considered to be lower compared to the reference biosphere case (1 m compared to 2 m); the thickness of the deep soil is then determined given the thickness of the topsoil as described above.

24 Reduced from the reference biosphere case to reflect a higher degree of organic material. Mineral soils are typically represented with grain densities of around 2,650 kg m^{-3} (as in the reference biosphere case). Pure organic matter will have a grain density closer to 1,000 kg m^{-3} (see e.g. Section 5.3 of SKB (2014)). However, the tundra soil is not a true organic soil as it will continue to have a reasonably high mineral content and has not developed from peat, so a relatively moderate adjustment is made compared to the reference biosphere case.

25 Derived from the total porosity, consistent with the reference biosphere case.

26 Not applicable – no diffusion through the permafrost layer.

Tab. 5-4: Biosphere characteristics for the drained farmland case

Footnotes discussing parameter values are included below the table.

Symbol	Units	Description	Value	Note
A_f	m^2	Surface area of the biosphere region	2.275E+6	1
d_{ETP}	$m\ a^{-1}$	Mean annual evapotranspiration rate	0.8	2
d_{PPT}	$m\ a^{-1}$	Mean annual precipitation rate	1	3
d_{capil}	$m\ a^{-1}$	Mean annual rate of capillary rise	0.1	4
$Irri_L$	$m\ a^{-1}$	Mean annual rate of irrigation with groundwater from the local aquifer	0	5
$Irri_W$	$m\ a^{-1}$	Mean annual rate of transfer from surface water to topsoil (including flooding)	0.2	6
F_{CL}	$m^3\ a^{-1}$	Flux of contaminated deep groundwater into local aquifer	1.04E+5	7
F_{CV}	$m^3\ a^{-1}$	Flux of contaminated deep groundwater into variably saturated zone	2.6E+4	7
F_{CW}	$m^3\ a^{-1}$	Flux of contaminated deep groundwater into surface water	0	8
F_{UL}	$m^3\ a^{-1}$	Flux of uncontaminated water into local aquifer	1.42E+6	9
F_{UV}	$m^3\ a^{-1}$	Flux of uncontaminated water into variably saturated zone	3.54E+5	9
F_{UW}	$m^3\ a^{-1}$	Flux of uncontaminated water into surface water	1.17E+10	10
Rel_L	-	Fraction of release into local aquifer	0.8	11
Rel_V	-	Fraction of release into variably saturated zone	0.2	11
Rel_W	-	Fraction of release into surface water	0	12
F_{DW}	$m^3\ a^{-1}$	Flux of water from deep soil into river (drainage ditches)	1.81E+6	13
F_{VS}	$m^3\ a^{-1}$	Flux of water from variably saturated zone through bed sediments	1E+6	14
F_{SV}	$m^3\ a^{-1}$	Flux of water from bed sediments into variably saturated zone	0	15
F_{VD}	$m^3\ a^{-1}$	Flux of water from variably saturated zone to deep soil	1E+6	16
F_{VL}	$m^3\ a^{-1}$	Flux of water from local aquifer to variably saturated zone	1.69E+5	17
F_{LE}	$m^3\ a^{-1}$	Groundwater flux from local aquifer to "elsewhere"	0	18
F_{VE}	$m^3\ a^{-1}$	Groundwater flux from variably saturated zone to "elsewhere"	0	18
m_e	$kg\ m^{-2}\ a^{-1}$	Erosion	0.27	19
m_{SL}	$kg\ m^{-2}\ a^{-1}$	Annual transfer to agricultural land (per unit area of land, not bed, sediment)	0.05	20

Symbol	Units	Description		Value	Note
m_{dep}	kg m^{-2} a^{-1}	Sedimentation onto topsoil		0	21
m_D	kg m^{-2}	Biomass of deep burrowing fauna (travelling between the deep soil and the topsoil)		0.05	22
ε_i	-	Total porosity for topsoil (T)		0.4	23
ρ_i	kg m^{-3}	Solid (grain) density of topsoil (T)		2000	24
θ_i	-	Volumetric moisture content	Topsoil (T)	0.3	25
			Deep soil (D)	0.35	26
			Var. sat. zone (V)	0.2	27

Notes for Tab. 5-4:

1 The same valley as in the reference biosphere case. Therefore, the overall area is the same (defined based on the area of the shallow local aquifer).

2 Increased compared to value of 0.6 m a^{-1} for the reference case to reflect the shallower water table, capillary rise, and higher volumetric moisture content of the deep soil.

3 Same as the reference biosphere case.

4 Seasonal fluctuations and proximity of the water table to the topsoil mean that there will be some advective exchange between the deep soil and topsoil, characterised as capillary rise, but encompassing a broader range of processes. The value is chosen so that capillary rise and flooding compensate for the absence of irrigation compared to the reference biosphere case, and is appropriate for sandy soils (Das 2010, Hansbo 1960). The value also reflects capillary rise for (fine) sandy material (e.g. Keeling et al. (2004)).

5 Greater proximity of groundwater to topsoil and associated capillary rise processes mean that a significant soil moisture deficit is unlikely, eliminating the need for irrigation.

6 Representative of flooding from surface water to topsoil; the value is chosen such that capillary rise and flooding compensate for the absence of irrigation compared to the reference biosphere case (i.e. they maintain the same soil moisture status in the topsoil as the reference biosphere case).

7 The total flux (m^3 a^{-1}) of potentially contaminated groundwater discharging into the local aquifer is the same as in the reference biosphere case because the context is essentially the same; however, the local aquifer is 25 m thick, as opposed to 20 m thick in the reference biosphere case. Thus, the release is divided between the "local aquifer" (20 m thick) and the "variably saturated zone" (5 m thick) compartments, weighted by their relative thickness (i.e. F_{CL} + F_{CV} for the drained farmland case is equal to F_{CL} for the reference biosphere case).

8 As for the reference biosphere case, the potentially contaminated groundwater is assumed to discharge into the local aquifer.

9 For the reference biosphere case, the uncontaminated flow into the local aquifer is based on (i) input from the aquifer upgradient plus (ii) assumptions about input from valley sides.

For the drained farmland case, the value is derived by scaling the input from the aquifer upgradient by the increased aquifer thickness, and assuming that the contribution from the valley sides remains the same. The resulting inflow is then divided between the local aquifer and variably saturated zone compartments by their relative thickness.

10 Same as the reference biosphere case.

11 Scaled by the relative thickness of the aquifer (20 m) and variably saturated zone (5 m) compartments.

12 Same as the reference biosphere case.

13 Calculated to ensure water balance in the deep soil.

14 Some discharge is assumed from the variably saturated zone to the river along the 3.5-km valley section, but this is taken to be notably less than the flow from the deep soil to surface water via drainage ditches; the water table is shallow and it is expected that most flow would be directed via the drainage ditches.

15 Same as the reference biosphere case.

16 Calculated to ensure water balance in the variably saturated zone.

17 Groundwater mixing/dispersion between the local aquifer and variably saturated zone, equal to 10% of the groundwater flow through the variably saturated zone.

18 Same as the reference biosphere case.

19 Taken to be the same as in the reference biosphere case; the degree of erosion may be lower in normal wetlands, but the area being modelled will have been drained for agriculture, so the erosion rate is expected to be similar to that for the reference biosphere case.

20 Some transfer of mass from bed sediment to topsoil is assumed, accompanying flooding; the value is higher than implied by the average sediment load and depth of flooding, reflecting that sediment loads would be elevated during flooding events. However, this remains a relatively small fraction of the gross erosion rate from the topsoil.

21 Same as the reference biosphere case.

22 The degree of bioturbation between the deep soil and the topsoil is taken to be reduced compared to the reference biosphere case due to the higher degree of saturation; a reduction by a factor of two is assumed.

23 Although a more organic soil is assumed for the drained farmland case, it is still dominantly a mineral soil, and the total porosity is taken to be identical because the reference biosphere case already assumes a relatively high degree of porosity for the topsoil.

24 Reduced from the reference biosphere case to reflect a higher degree of organic material; mineral soils are typically represented with grain densities of around 2,650 kg m^{-3} (as in the reference biosphere case). Pure organic matter will have a grain density closer to 1,000 kg m^{-3} (see e.g. Section 5.3 of SKB (2014)). However, the drained farmland soil is not a true organic soil as it is taken to have developed from floodplain soils rather than developed from peat, so a relatively moderate adjustment is made compared to the reference biosphere case.

25 Same as the reference biosphere case.

26 Increased compared to the reference biosphere case to reflect partial saturation and seasonal variation.

27 Increased compared to the reference biosphere case to reflect full saturation.

5.2 Exposure group data

Dietary data for the reference biosphere, warmer-drier climate and drained farmland cases are given in Tab. 5-5. Dietary data for the cold climate case are given in Tab. 5-6. Other exposure related data are provided in Tab. 5-7.

Tab. 5-5: Dietary data for the reference biosphere, warmer-drier climate and drained farmland cases

The data are taken to be expressed on a fresh-weight basis. The overall energy intake is discussed in Tab. 5-7. Further footnotes discussing parameter values are included below the table.

Foodstuff	**Energy content, kJ kg^{-1}**	**Intake rate, kJ a^{-1}**	**Fraction of dietary energy intake -**	**Ingestion rate[1], g day^{-1}**	**Local fraction, -**		**Notes**
					Reference, warmer-drier	Drained farmland	
Beef	8730	1.89E+5	0.065	59.5	1.0	1.0	2
Milk and dairy produce	2820	1.35E+6	0.462	1310	1.0	1.0	3
Fish meat	5710	3.39E+4	0.012	16.8	0.1	0.1	4
Eggs	6550	5.21E+4	0.018	22.0	1.0	0.0	5
Chicken meat	8730	1.89E+5	0.064	58.6	1.0	0.0	2
Grain	13,800	7.66E+5	0.262	152	1.0	0.0	6
Root vegetables	3000	1.44E+5	0.049	131	1.0	1.0	6
Green vegetables	1130	6.44E+4	0.022	156	1.0	1.0	6
Fruit	2200	1.33E+5	0.046	167	1.0	0.0	6

Notes for Tab. 5-5:

1 Daily ingestion rate calculated for illustrative purposes from the total energy intake (2.92E+6 kJ a^{-1}), energy content and fraction of dietary energy intake and given to three significant figures.

2 The energy content of meat is calculated from energy and mass using data from p. 22 of BAG (1998). The energy content of beef and chicken is assumed to be identical.

The annual energy from meat is based on BAG (1998) and equates to about 43 kg a^{-1}. This is split evenly between beef and chicken; the food fraction for chicken is then rounded down to ensure that the sum of food fractions equals unity.

For the drained farmland case, chickens are assumed to have been obtained from elsewehere, so the local fraction is set to zero.

3 The energy content of milk is based on p. 17 of SVE (1993).

In previous assessments, including Nagra (2010) and Nagra (2014), the fractional energy intake from milk and dairy produce is calculated as the remaining fraction after accounting for all other foodstuffs. This resulted in an energy fraction of 0.462.

4 The energy content of fish is calculated from energy and mass data from p. 22 of BAG (1998). The annual energy from fish is based on BAG (1998) and equates to about 6 kg a^{-1}.

On the basis that only around 2% of fish consumed in Switzerland is produced domestically (BFS 2014), and that the river stretch considered in biosphere modelling is relatively short, it is considered unreasonable for the local population to obtain 100% of their fish intake from the local river.

Therefore, consistent with Nagra (2014), the local fraction is set to 10% for fish. This value is three times higher than the per capita domestic production of freshwater fish in 2013 (BFS 2014) and is, therefore, still considered a pessimistic value and representative of a local population making reasonable maximum use of local food sources.

5 The energy content of eggs is calculated from energy and mass using data from p. 22 of BAG (1998). The annual energy from eggs is based on BAG (1998) and equates to about 8 kg a^{-1}.

For the drained farmland case, chickens are assumed to have been obtained from elsewehere, so the local fraction is set to zero.

6 The energy content of cereals, root vegetables, green vegetables and fruit are calculated from energy and mass using data from p. 22 of BAG (1998). The annual energies from these crops are based on BAG (1998) and equate to about 55, 48, 57 and 61 kg a^{-1}, respectively.

For the drained farmland case, grain and fruit are assumed to have been obtained from elsewhere.

Tab. 5-6: Dietary data for the cold climate case

Footnotes discussing parameter values are included below the table.

Foodstuff	Fraction of dietary energy intake	Local fraction	Notes
Local meat	0.211	1.0	1
Other meat	0.211	0.0	1
Milk and dairy produce	0.220	1.0	2
Fish meat	0.012	0.1	3
Eggs	0.018	0.0	4
Grain	0.211	0.0	5
Root vegetables	0.049	0.1	6
Green vegetables	0.022	0.1	6
Fruit	0.046	0.1	6

Notes for Tab. 5-6:

1 Overall intake of meat is increased compared to the reference biosphere case, reflecting behaviours of herding communities in cold climates, e.g. Brustad et al. (2008). 50% of meat is assumed to be produced locally; this is taken to derive solely from the modelled biosphere area, which is notably pessimistic given the cold climate conditions and low productivity. The remaining 50% of meat is taken to derive from elsewhere.

2 Energy intake from milk and dairy produce is lowered compared to the reference biosphere case to accommodate higher energy from meat; however, all of the milk and dairy produce is pessimistically considered to derive from local livestock.

3 Same assumptions as for the reference biosphere case.

4 Chickens and eggs are taken to be obtained from elsewhere.

5 Energy intake from grain is reduced compared to the reference biosphere case to accommodate the extra intake from meat. It is not considered viable to grow cereal crops in cold climate conditions, so it is taken to be obtained from elsewhere.

6 The energy intake from root vegetables, green vegetables and fruit is taken to be the same as in the reference biosphere case. The low productivity and/or small area mean that 10% is assumed to be derived locally for the cold climate case.

Tab. 5-7: Other exposure-related data

Footnotes discussing parameter values are included below the table.

Symbol	Units	Description	Value	Note
a_r	kg m^{-3}	Background dust concentration	5.0E-8	1
a_f	kg m^{-3}	Occupational/elevated dust concentration	1.0E-5	1
E_0	kJ a^{-1}	Calorific value of food consumed annually	2.92E+6	2
f_{well}	-	Fraction of drinking water taken from the well in the local aquifer	1	3
f_{filter}	-	Filtration factor for water consumption	0	4
I_{air}	m^3 a^{-1}	Annual inhalation rate of air	8,020	5
I_{fluid}	m^3 a^{-1}	Annual intake of liquids from all sources	1.062	6
O_f	-	Fraction of year spent at high dust concentrations	0	7
v_A	m a^{-1}	Mean annual wind velocity	4.1E+7	8

Notes for Tab. 5-7:

1 Estimate, based on data from Linsley (1978).

2 The value includes the energy from all food that is considered in the diet for biosphere modelling. Sugar is not included in this diet, because the production process of sugar will remove most contamination. The value of 2.92E+6 kJ a^{-1} (8,000 kJ d^{-1}) can be derived as follows: the energy content of the average consumption of food per person for the years 1994 – 1995 in Switzerland was 12,395 kJ d^{-1} (p.22 of BAG (1998)). This is significantly more than the recommendations for daily intake and would imply an increase in weight of the average Swiss population. It can be concluded that part of the food is lost during preparation or not eaten for other reasons. BAG (1998) (p. 31) argues that the losses might be in the order of 20 – 25%. When assuming a loss of 25% and subtracting sugar for the reasons given above, average intake results in around 7,800 kJ d^{-1}. This value is rounded up to 8,000 kJ d^{-1}.

3 Conservative assumption.

4 Conservative assumption.

5 According to ICRP Publication No. 23 (p. 346 of ICRP (1975)), the following breathing rates are used: a) during phases of resting, 6.0 L min^{-1} for an adult woman and 7.5 L min^{-1} for an adult man, and b) during phases of light activity, 19 L min^{-1} for an adult woman and 20 L min^{-1} for an adult man. Taking the mean of the breathing rates for women and men, and assuming 8 hours of resting and 16 hours of light activity per day, results in an annual inhalation rate of 8020 m^3 a^{-1}.

6 This value corresponds to a daily intake of 2.9 L d^{-1}. It is a pessimistic assumption. According to ICRP Publication No. 23 (p. 360 of ICRP (1975)), the average total fluid intake of an adult woman is 1.4 L d^{-1} and that of an adult man 1.95 L d^{-1}. The fluid intake of 1.1 m^3 a^{-1} corresponds to a drinking water consumption of 0.6 m^3 a^{-1} and a milk consumption rate of 0.5 m^3 a^{-1}.

7 It is assumed that the members of the critical group do not engage in heavy outdoor work at high dust concentrations (e.g. ploughing). This is consistent with the assumed diet.

8 4.1E+7 m a^{-1} is equal to 1.3 m s^{-1}. This is a typical value for the wind speed in Northern Switzerland.

Tab. 5-8: Other parameter modifications for the cold climate case

Footnotes discussing parameter values are included below the table.

Symbol	Units	Description		Value	Note
Y_{Crop}	kg fw m^{-2}	Fresh weight yield of the crop	Green vegetables	1.5	1
			Root vegetables	2.0	1
f_{Well}	-	Fraction of drinking water obtained from a well for consumption by humans		0.0	2
f_A	-	Fraction of drinking water obtained from a well for consumption by animals		0.0	3

Notes for Tab. 5-8:

1 Yields under cold climate conditions are taken to be halved compared to the reference biosphere case.

2 Drinking water for the local population is taken from surface water, which is typical for communities living in permafrost-affected regions (see Lemieux et al. (2020)) because of its abundance and relative ease of access.

3 Consistent with drinking water for humans, 100% of the drinking water for animals is assumed to come from the local surface water.

5.3 General crop and animal data

Element-independent parameter values relating to crops are presented in Tab. 5-9. These are generally consistent between the different calculation cases. An adjustment to crop yield is required for the cold climate case and is specified in Tab. 5-8.

Element-independent parameter values relating to livestock are given in Tab. 5-10. An adjustment to the drinking water fraction is required for the cold climate case and is specified in Tab. 5-8.

Tab. 5-9: Element-independent crop data for the reference, warmer-drier climate and drained farmland cases

Footnotes discussing parameter values are included below the table.

Symbol	Units	Description		Value	Notes
B_{crop}	kg dw m^{-2}	Above-ground dry standing biomass at the time of irrigation	Pasture	0.7	1
			Grain	1.5	
			Green vegetables	1.2	
			Root vegetables	1	
			Fruit	0.8	
μ_{crop}	m^2 kg^{-1}	Interception factor for plants, expressed on a dry weight basis		3	2
Y_{crop}	kg fw m^{-2}	Fresh weight yield of the crop	Pasture	1.2	3
			Grain	0.61	
			Green vegetables	3.0	
			Root vegetables	4.0	
			Fruit	2.5	

Symbol	Units	Description		Value	Notes
f_{ext}	-	Fraction of the external intercepted contamination that is retained on the edible part of the plant after food processing	Pasture	1	4
			Grain	0.25	5
			Green vegetables	0.5	6
			Root vegetables	0	7
			Fruit	0.15	8
f_{int}	-	Fraction of the contamination in the internal edible part of the plant that remains after food processing		1	9
f_{trans}	-	Fraction of the translocated contamination that is associated with the edible part of the plant		1	10
S_{crop}	kg kg^{-1}	Soil contamination of crops (assumes wet/saturated soil)	Pasture	0.1	11
			Grain	9E-5	
			Green vegetables	0.0002	
			Root vegetables	0	
			Fruit	0.00025	
f_{soil}	-	Fraction of external soil contamination that is retained on the edible part of the plant after food processing		1	12
t_1	a	Time between start of irrigation and harvest		0.25	13
t_2	a	Time between end of irrigation and harvest	Pasture	0.02	14
			Grain	0.075	
			Green vegetables	0.02	
			Root vegetables	0.04	
			Fruit	0.02	
Z	-	Ratio of weight of fresh pasture (i.e. grass) to hay		5	15

Notes for Tab. 5-9: n/a indicates not applicable.

1 Based on irrigation close to maturity and consideration of growth functions given in Section 3.4 of Walke et al. (2021) and Bolinder et al. (1997). Value for grain reflects wheat, that for green vegetables reflects cabbages, the value for root vegetables reflects potatoes and for fruit, it reflects shrub fruit (e.g. raspberries).

2 Based on discussion in Section 3.6.1 of Walke et al. (2021) associated with wet deposition.

3 Typical values based on data of SBV (2000). The value for pasture reflects hay (i.e. partially dried) and reflects two cuttings per year.

Note that yields are adjusted for the cold climate case, as specified in Tab. 5-8.

4 Consumed by animals without processing.

5 Fraction of intercepted contamination on grain is based on a harvest index of about 0.5, e.g. Kemanian et al. (2007). This conservatively ignores the greater surface area of leaves per unit of biomass and the associated higher affinity of leaves for interception in comparison to grain. A food processing retention factor of 0.5 is adopted based on the range given in Table 71 of IAEA (2010) for milled flour and bran.

6 All externally intercepted contamination conservatively taken to be associated with the plant produce. A food processing retention factor of 0.5 is adopted based on the average reported for washed vegetables in Table 70 of IAEA (2010).

7 None of the external intercepted contamination is associated with the roots.

8 Based on yield of 0.1 kg dw m^{-2} compared to a stem and leaf biomass of 0.7 kg dw m^{-2} and rounded up (Table 3-15 of Walke et al. (2021)). Additional reduction due to food preparation is ignored.

9 Conservatively taken to be 100%.

10 Conservatively taken to be 100%, given that translocation fractions are typically defined based on absorption and translocation to edible tissues.

11 Values for grain, green vegetables and fruit based on consideration of IAEA (1994), giving due consideration to fresh and dry weight. Root vegetables are taken to be peeled, thereby removing all external contamination. The value for pasture is based on considerations of IAEA (1994) and Whitehead (2000) (pp. 88 – 89).

12 Conservatively taken to be 100% to avoid any double-counting in the definition of the surface contamination factor (which is zero for root vegetables).

13 Irrigation assumed to commence three months before harvest, equivalent to starting irrigation at the beginning of summer and harvesting crops at the end of summer.

14 Values for pasture, grain, green vegetables and root vegetables from Table C27 of IAEA (2003). Fruit cautiously assumed to take the same value as green vegetables and pasture. Equates to 7 days for green vegetables, fruit and pasture, 14 days for root vegetables and 28 days for grain.

15 The dry matter content of grass is in the order of 20% (p. 43 of Laur (1937)), depending on grass variety and time of cutting. The dry matter content of hay is about 85% (pp. 45 – 46 of Laur (1937)), again depending on grass variety and time of cutting and also on the degree of drying. With these numbers, 100 kg of grass (20 kg dry matter and 80 kg water) yields 23.5 kg of hay (20 kg dry matter and $15/85 \times 20$ kg = 3.5 kg water). The ratio of the weight of grass to that of hay is therefore 100 kg/23.5 kg = 4.25. The same calculations can be performed with other data. Ashman & Puri (2002) (p. 143) give dry matter contents of 15-20% for fresh grass and 86% for hay. Taking these percentages leads to ratios Z of 4.3 and 5.7. The average of the two ratios is 5.

Tab. 5-10: Element-independent data for animals

Footnotes discussing parameter values are included below the table.

Symbol	Units	Description		Value		Note
				Reference & warmer-drier	Drained farmland	
f_A	-	Fraction of animal water consumption taken from the well in the local aquifer	Cattle	1	0	1
			Chickens	1	0	
I_{pc}	kg day^{-1}	Consumption rate of fodder by animals, dry weight	Cattle (hay)	20		2
			Chickens (grain)	0.07		3
I_{wc}	m^3 day^{-1}	Consumption rate of water by animals‡	Cattle	0.03		4
			Chickens	0.0002		5
w_{egg}	g egg^{-1}	Average weight of an egg		48		6
η_{egg}	kJ	Average energy content of an egg		314		7
w_{milk}	kg m^{-3}	Conversion from weight to volume for milk		1,000		8

Notes for Tab. 5-10:

1 Conservative assumption for the reference and warmer-drier climate cases.

For the drained farmland case, livestock are assumed to obtain drinking water from surface water rather than from a well, since the biosphere area is wetter and groundwater is closer to the surface.

2 The grass consumption rate for cows in Switzerland is about 100 kg d^{-1} (Bundi & EIR (1984), p. 33). Assuming that the weight ratio of grass to hay is 5 (see Tab. 5-9), this results in I_{pc} = 20 kg d^{-1}. In comparison, the expected dry matter intake of dairy cows according to IAEA (1994) (p. 33) is 16.1 kg d^{-1}, with a range of 10 – 25 kg d^{-1}. When assuming the water content of hay as 15%, the consumption rate of 20 kg d^{-1} corresponds to a dry matter intake of 17 kg d^{-1}.

3 Value taken from Bundi & EIR (1984), p. 33. The value is equal to the expected dry matter intake of chickens according to IAEA (1994) (p. 33). The expected dry matter intake of laying hens according to IAEA (1994) (p. 33) is slightly higher, namely 0.1 kg d^{-1}.

4 Value taken from Bundi & EIR (1984), p. 33.

5 Value taken from Bundi & EIR (1984), p. 33. The value is in the middle of the range given by IAEA (1994) (p. 33) for the water intake of laying hens and chickens (0.1-0.3 l d^{-1}).

6 The average weight of the contents of an egg is taken to be 48 g; this excludes the weight of the shell, noting that the average weight of an egg including the shell is around 60 g.

7 Based on the energy content of eggs (see Tab. 5-6) of 6,550 kJ kg^{-1} and an average weight of egg contents of 48 g (see above).

8 The density of cow milk ranges between 1.02 and 1.04 kg L^{-1} (Sherbon 1988). This is rounded to 1000 kg m^{-3}, providing an adequate degree of precision in this context.

5.4 Generic element-dependent data

The generic element-dependent parameter values are presented in the following subsections:

- sorption (Section 5.4.1);
- degassing rate from soil (Section 5.4.2);
- transfer factor from soil to crop (Section 5.4.3);
- weathering loss term for externally intercepted contaminants (Section 5.4.4);
- translocation rate from external intercepted contamination to edible crop (Section 5.4.5);
- transfer factor from feed to beef (Section 5.4.6);
- transfer factor from feed to milk (Section 5.4.7);
- transfer factor from feed to eggs (Section 5.4.8);
- transfer factor from feed to chicken (Section 5.4.9); and
- transfer factor from surface water to fish (Section 5.4.10).

Each parameter includes an introductory discussion describing its key considerations. The corresponding parameter values are presented in a table. Justification for parameter values and associated distributions are provided as footnotes to the tables, along with associated references.

Best-estimate parameter values are provided, consistent with Section 2.3; ranges for sensitivity analyses are discussed in Section 6.3.2.

For transfer factors, the values are rounded to one significant figure. A greater level of precision is inappropriate, given the degree of uncertainty surrounding the parameter values.

Most of the radionuclides being modelled are radioisotopes of trace elements in the biosphere and can be represented with the same mathematical modelling approach. As a radioisotope of an element that is fundamental to biogeochemistry, C-14 is an exception and requires special consideration in modelling C-14 transport in the biosphere and its uptake by plants as given in Guillemot et al. (2024). This modelling approach delivers parameter values that allow the migration, retention and uptake of C-14 in the biosphere to be appropriately modelled and is referenced in justifying parameter values for C-14 in the subsections below.

5.4.1 Sorption

Sorption properties for biosphere materials have been subject to a full, systematic review and update in preparation for the RBG assessment and are described in Metcalfe et al. (2023). The review provides reference, upper and lower guideline values for the equilibrium sorption coefficient (K_d) for a set of material types. Mapping from compartments to the sorption materials is provided in Tab. 5-11.

Tab. 5-11: Mapping from biosphere model compartment to sorption materials

Reference values from Metcalfe et al. (2023) were used, unless stated in the notes.

Compartment	Mapping	Notes
Topsoil	Fine, higher organic soil	Topsoil K_d for the drained farmland and cold climate cases use twice the reference value to reflect higher degree of organic matter content
Deep soil	Fine, low organic soil	
Var. sat. zone	Coarse, low organic aquifer	
Aquifer	Coarse, low organic aquifer	
River bed sediment	Coarse, low organic riverbed	
Surface water	Fine, higher organic river	

K_d values for C-14 in the biosphere are justified by special consideration, as discussed in Guillemot et al. (2024). The resulting values are given in Tab. 5-12. A consistent value of 0.015 $m^3\ kg^{-1}$ is used for most compartments, based on consideration of the content of calcium carbonate and the associated exchangeable fraction. The K_d value for the topsoil is enhanced compared to the other compartments, reflecting a greater degree of retention on soil organic matter, although the modelling summarised in Guillemot et al. (2024) indicates that there is little distinction between the different calculation cases.

Tab. 5-12: K_d values for C-14 for the different calculation cases, $m^3\ kg^{-1}$

Based on modelling and discussion summarised in Guillemot et al. (2024); these represent the average values across the range of crops modelled in each case.

Compartment	Reference	Warmer-drier	Cold climate	Drained farmland
Topsoil	0.026	0.026	0.026	0.025
Deep soil	0.015	0.015	0.015	0.015
Var. sat. zone	0.015	0.015	0.015	0.015
Aquifer	0.015	0.015	0.015	0.015
River bed sediment	0.015	0.015	0.015	0.015
Surface water	0.015	0.015	0.015	0.015

5.4.2 Degassing rate from soil

The degassing rates from topsoil to elsewhere for C-14 are given in Tab. 5-13 and are based on modelling summarised in Guillemot et al. (2024). Inclusion of degassing from soil for C-14 is well justified (e.g. Thorne et al. (2023)). The degassing rates for C-14 are applied as both a gas loss term to elsewhere, λ_{TE}, as described in Section 4.2.3.5 and as a degassing rate, λ_{dg}, contributing to a concentration in the atmosphere over the soil, as given in Equation 58 in Section 4.2.4.9.

Degassing losses for radionuclides other than C-14 are ignored.

Tab. 5-13: Degassing rates from topsoil for C-14, λ_{TE}, a^{-1}

Based on modelling and discussion summarised in Guillemot et al. (2024); these represent the average values across the range of crops modelled in each case.

Case	Degassing rate, a^{-1}
Reference	1.1
Warmer-drier climate	1.1
Cold climate	1.2
Drained farmland	0.71

As with all potentially volatile radionuclides aside from C-14, radon emanation from soil is ignored. Radon occurs naturally and is of potential interest because it can be generated from Ra-226 that has travelled to the biosphere and/or ingrows within the biosphere from the disposed inventory. Outdoor dispersion means that potential exposure would be limited and is ignored on that basis. Potential indoor exposure to radon, where ventilation rates would be lower, is ignored because dwellings would not be constructed over areas affected by irrigation, groundwater discharge or flooding. Potential radon exposure arising from degassing from use of the shallow groundwater indoors (e.g. during washing and laundry) is taken to be insignificant.

5.4.3 Transfer factor from soil to crop

The soil-to-crop transfer factor represents equilibrium concentrations within edible plant tissues as a result of radionuclide uptake from the soil based on fresh weight (fw) of plant tissue and dry weight (dw) of soil; it therefore has units of (Bq kg^{-1} fw crop) per (Bq kg^{-1} dw soil).

Extensive data are provided in Tables 17, 18 and 19 of IAEA (2010). These values are given on the basis of a dry-weight plant and dry-weight soil in IAEA (2010) and have therefore been scaled by the ratio of dry-weight plant to fresh-weight plant for use here. This information is given in Tables 82 to 85 in Appendix I of IAEA (2010); the dry-to-fresh weight ratios assumed here are summarised in Tab. 5-14.

Tab. 5-14: Crop-dependent values for the ratio of dry weight to fresh weight

Crop	Dry weight:fresh weight ratio assumed (%)	Notes
Pasture	20	Consistent with Tab. 5-9 and Table 84 of IAEA (2010), which also gives values of 26% for grass silage and 86% for grass hay. The drying of hay substantially reduces its water content.
Grain	88	Value based upon wheat in Table 82 of IAEA (2010).
Green vegetables	10	Based on an average of cabbage, lettuce, leek, onion, spinach and cauliflower in Table 82 of IAEA (2010).
Root vegetables	20	Based on consideration of beetroot, carrot, potato and turnip in Table 82 of IAEA (2010), with additional weight given to potatoes as a staple of the diet.
Fruit	15	Based on an average of apple, pear, grape and strawberry in Table 83 of IAEA (2010).

IAEA (2010) has been used in preference to other sources, particularly where the values are supported by several samples or more. Where available, the fruit is based upon herbaceous fruit data provided in IAEA (2010). For many of the elements where data were not available in IAEA (2010), the values are based on Walke et al. (2013b).

Where the available data suggest very similar values for different types of plants and where distinctions between those values are not supported by a large number of samples, the same value has been preferentially adopted for different plant types, given that the typical level of uncertainty surrounding soil-to-plant transfer factors spans several orders of magnitude (e.g. Sheppard (2005)).

The values are given in Tab. 5-15.

Tab. 5-15: Soil-to-crop transfer factor, K_{crop}, (Bq kg^{-1} fw crop) per (Bq kg^{-1} dw soil)

Footnotes discussing parameter values are included below the table.

Element	Pasture	Grain	Green vegetables	Root vegetables	Fruit	Notes
C	1.7E+00	7.9E+00	Ref.: 8.2E-01 Cold: 8.1E-01	Ref.: 1.8E+00 Cold: 1.7E+00	8.4E-01	1
Al	3E-04	3E-05	3E-05	3E-05	3E-05	2
Si	1E-02	1E-02	1E-02	1E-02	1E-02	3
Cl	3E+01	3E+01	3E+01	3E+01	3E+01	4
Ca	1E+00	1E+00	1E+00	1E+00	1E+00	5
Ti	1E-02	1E-02	1E-02	1E-02	1E-02	6
Fe	4E-04	2E-04	2E-04	2E-04	2E-04	7
Co	1E-02	1E-02	1E-02	1E-02	1E-02	8
Ni	2E-02	2E-02	2E-02	2E-02	2E-02	9

Element	Pasture	Grain	Green vegetables	Root vegetables	Fruit	Notes
Se	7E-03	6E-02	4E-03	5E-03	3E-03	10
Sr	3E-01	1E-01	1E-01	1E-01	1E-01	11
Zr	2E-03	9E-04	6E-04	6E-04	6E-04	7
Nb	4E-02	1E-02	3E-03	3E-03	3E-03	7
Mo	7E-01	7E-01	6E-02	6E-02	6E-02	12
Tc	1E+01	1E+01	1E+01	1E+01	1E+01	13
Pd	4E-02	4E-02	4E-02	4E-02	4E-02	14
Ag	1E-04	1E-04	1E-04	1E-04	1E-04	15
Sn	1E-02	1E-02	1E-02	1E-02	1E-02	16
I	3E-02	3E-02	3E-02	3E-02	3E-02	17
Cs	5E-02	3E-02	6E-03	8E-03	3E-03	18
Sm	2E-02	2E-02	2E-02	2E-02	2E-02	19
Ho	2E-02	2E-02	2E-02	2E-02	2E-02	19
Hg	8E-03	8E-03	8E-03	8E-03	8E-03	20
Pb	1E-02	1E-02	1E-02	1E-02	1E-02	21
Po	1E-02	1E-03	1E-03	1E-03	1E-03	22
Ra	1E-02	1E-02	1E-02	1E-02	1E-02	23
Ac	3E-04	3E-05	3E-05	3E-05	3E-05	24
Th	2E-04	2E-03	1E-04	1E-04	1E-04	25
Pa	2E-04	2E-03	1E-04	1E-04	1E-04	26
U	9E-03	5E-03	2E-03	2E-03	2E-03	27
Np	1E-02	3E-03	3E-03	3E-03	3E-03	28
Pu	1E-04	1E-05	1E-05	1E-05	1E-05	29
Am	3E-04	3E-05	3E-05	3E-05	3E-05	30
Cm	3E-04	3E-05	3E-05	3E-05	3E-05	30
Cf	3E-04	3E-05	3E-05	3E-05	3E-05	31

Notes for Tab. 5-15:

1 Based on modelling of C-14 in the soil-plant-atmosphere system, summarised in Guillemot et al. (2024). Note that the values for carbon are specified as two significant figures to reflect the supporting modelling and to ensure that the dynamic behaviour of C-14 is consistent in the two models.

The supporting modelling gives the same values as used for the reference biosphere, warmer-drier climate and drained farmland cases (denoted “Ref.” in the table above). A slightly different value is derived for the crops relevant to cold climate cultivation (denoted “Cold” in the table above).

2 Al occurs only in the 3+ state and is generally poorly bioavailable. One of the 3+ higher actinides, Am, is used as an analogue.

3 Although Si is an essential trace element, it does not have a biogeochemical cycle comparable to that of carbon. Furthermore, the stable element data are not very helpful, because of the predominance of silicates (and particularly aluminosilicates) in the environment. In part, due to the abundance of data for Sn, which has a similar chemistry as Si and forms a variety of organic complexes and is accumulated to some degree in mineralised tissues, Sn is used as the analogue.

4 Table 18 of IAEA (2010) includes some limited data for a wide range of plant types. A cautious value of 30 is used across all plant types to reflect uncertainty in the value and also to reflect that in an inland, upland area like Switzerland, the soils are likely to be chloride-deficient and higher transfer factors will apply because stable chloride levels in plants are maintained quasi-homeostatically.

5 Limited data are available for Ca, although average values of about 9 and 20 are reported on a dry-weight basis in Table 17 of IAEA (2010) for stems and shoots of cereals and stems and shoots of leguminous vegetables. A geometric average of these values converted to a fresh-weight basis for the plants implies a value of about 1. It is noted that this is typically an order of magnitude greater than the values for Sr, with which a similarity of a factor of one to two would be expected. This implies that this is a conservative assumption.

6 Ti has low bioavailability. Its only stable environmental oxidation state is 4+, and compounds such as tetrachloride hydrolyse rapidly to oxides of the element. Sn is used as an analogue.

7 Based on Table 17 of IAEA (2010). The similar nature of the values means that the same value is used for green and root vegetables, based on the average of the two. No value is available for fruit, so the vegetable value is used. No value is available for pasture so the grain value is conservatively used.

8 Consideration of a wide range of plant types in Table 17 of IAEA (2010) supports a value of 1E-2 on a fresh-weight basis across all plant types.

9 Based on consideration of Table 17 of IAEA (2010) and discussion in Section 5.5.2 of Thorne & Walke (2020).

10 IAEA (2010) does not contain recommendations for Se. However, a comprehensive peer-reviewed discussion appears in Pérez-Sánchez et al. (2012). The values given here are based on sources discussed therein, in particular Uchida S et al. (2007a), Uchida S et al. (2007b) and Tsukada & Nakamura (1998).

11 Table 17 of IAEA (2010) indicates that a value of 0.1 is appropriate for a range of plant types. A value of 0.3 is supported for pasture, given the large number of associated samples (172). Results for fruit presented in Table 19 of IAEA (2010) are at odds (i) with values for other plants and (ii) with an expected similarity with Ca. Given this uncertainty, a value of 0.1 is conservatively adopted for fruit.

12 Based on Table 17 of IAEA (2010). The similar nature of the values means that the same value is used for green and root vegetables, based on the average of the two. No value is available for fruit, so the vegetable value is used. No value is available for pasture so the grain value is conservatively used.

13 Table 18 of IAEA (2010) indicates that a value of 10 is appropriate for a range of plant types. The low value of about 1 for grain on a fresh-weight basis is only based on two results and is discounted.

14 Table 3-38 of Walke et al. (2021).

15 Based on Table 17 of IAEA (2010) values for leafy vegetables, non-leafy vegetables and root crops.

16 Table 18 of Walke et al. (2013b).

17 Based on review in Section 4.3 and recommendation in Table 4-21 of Thorne & Limer (2009), which includes consideration of IAEA (2009) and is in agreement with the single value given for I to fruit in Table 19 of IAEA (2010). It is unclear why the data presented in Table 20 of IAEA (2009) are not summarised in Table 17 of IAEA (2010).

18 Table 17 of IAEA (2010). Note that the uptake of Cs by plants is dependent on the potassium status of the soil and is therefore affected by agricultural practice. Application of fertiliser will increase the potassium status of the soil and decrease the uptake of Cs.

19 Values for lanthanides would be expected to be similar. No values for Sm or Ho are presented in IAEA (2010) so these values are based on data for Pm in Table 17 of IAEA (2010) by analogy.

20 Concentration ratio for sand and loam soils are used from Table 3-38 of Walke et al. (2021). That table gives a value of 2E-3 for clay soils.

21 Data in Table 17 of IAEA (2010) indicate limited distinction between plant types for Pb, which is supported by Thorne & Mitchell (2011). The value is based on the data given in Table 17 of IAEA (2010).

22 Based on relatively limited data for Po in Table 17 of IAEA (2010). The data suggest that values for grain and vegetables are similar, so no distinction is made and a value of 0.001 is used for these crops and fruits. The data indicate that a higher value may be appropriate for pasture, so a value of 0.01 on a fresh-weight basis is used, although Section 2.13.2 of Thorne (2008) notes that this higher value may be due to the confounding factor of atmospheric deposition to pasture.

23 Based on relatively extensive data in Table 17 of IAEA (2010), which indicates a value of 0.01 on a fresh-weight basis across a range of plant types. No data are available in IAEA (2010) for fruit, however, it is reasonable to adopt the same value used for all other plant types.

24 No data for Ac is given in IAEA (2010). Consistent with Walke et al. (2013b) and Thorne and Walke (2020), transfer factors for actinium are identical to those for Am and Cm.

25 Based on relatively extensive data in Table 17 of IAEA (2010). The data suggest a distinction between grain and other crops, which is reflected here. No values are provided for fruit in IAEA (2010), so the vegetable value is used. A notably higher value is given for pasture in Table 17 of IAEA (2010); however, this is considered conservative and may reflect a contribution from external contamination, as noted in Section 2.17.2 of Thorne (2008).

26 IAEA (2010) provide no data for Pa. Consistent with Thorne & Walke (2020) and Walke et al. (2013b), transfer factors for Pa are assumed to be identical to those for thorium.

27 Based on extensive data in Table 17 of IAEA (2010). No data are presented for fruit, which is taken to have the same transfer factor as for green and root vegetables.

28 Based on extensive data in Table 17 of IAEA (2010), which indicates little difference between crops, but supports a higher value for pasture. No data are presented for fruit, which is taken to have the same transfer factor as for other crops.

29 Based on extensive data in Table 17 of IAEA (2010), which indicates little difference between crops and fruit, but supports a higher value for pasture.

30 Biogeochemical similarities mean that Am and Cm should be considered together (Section 20 of Thorne & Walke (2020)). Relatively extensive data for both are given in Table 17 of IAEA (2010), which supports a value of about 3E-5 on a fresh-weight basis for crops and fruit and a value of about 3E-4 for pasture. In considering the value for crops and fruit, additional weight has been given to the values for grain, given the relatively large number of supporting samples.

31 Biogeochemical similarity with Am and Cm, which means that the same values could be adopted for Cf.

5.4.4 Weathering loss term for externally intercepted contaminants

The weathering loss term for externally intercepted contaminants represents the loss rate to soil of radionuclides that have been intercepted from irrigation water on the external surfaces of crops. The data for the parameter are presented on a per-year basis, a^{-1}.

Once deposited on vegetation, contaminants are lost from plants by leaching or cuticular abrasion. The increase of biomass during growth does not cause a loss of contaminants; however, it does lead to a decrease in concentration due to growth dilution. Although growth (and hence growth dilution) cannot be described by a simple exponential function, at least in some parts of the growth curve, the growth rates observed are equivalent to half-lives of 10 to 50 days (Thiessen et al. 1999). Growth dilution is often included within weathering loss, and the rate of reduction of concentration is often expressed in terms of the weathering half-life.

IAEA (2010) provides some element-specific recommendations for weathering loss rates which include growth dilution[12], in particular for Cs, I, Pu and Sr, but only for a limited number of crop types. The chapter on weathering in IAEA (2009) features weathering loss data as a function of plant-growth stages. These data include a few short weathering half-lives relating to contamination a few days before harvest. Weathering will include shorter and longer-term processes; the short half-lives in IAEA (2009) are almost certainly because the associated studies will have tended to emphasis short-term losses.

Table 6 of IAEA (2010) shows no consistent trend in values between different elements or different crop types. The most that can be said is that the arithmetic mean values range between 10 and 43 days, and that the full ranges (when given) are between 7.9 and 49 days. Thus, the data presented in IAEA (2010) are consistent with the recommendations by Walke et al. (2021), which consider that there is no strong argument for element-specific weathering loss rates.

Walke et al. (2021) note that, overall, weathering half-lives, including growth dilution, generally range between 5 and 50 days, though values of up to 100 days can be recorded. Walke et al. (2021) recommend a weathering half-life of 20 days, excluding growth dilution. Adjusting this value for inclusion of growth dilution, a reference weathering half-life of 15 days is therefore used for all elements, with the exception of C, and crop types. The reference value corresponds to a weathering rate of 17 a^{-1}.

Given its status as a radioisotope of an element that represents a fundamental building block of biological systems, a model specific to C-14 is used by Nagra to support its representation in the biosphere (Guillemot et al. 2024). Interception of C-14 is of limited importance for carbon, because carbon is predominantly taken up by plants from the canopy atmosphere for use in photosynthesis. Interception and weathering are, therefore, excluded from Nagra's model for C-14, and the use of a rapid rate for weathering is appropriate.

The weathering loss terms for contaminants intercepted on external surfaces of plants are summarised in Tab. 5-16.

Tab. 5-16: Weathering loss term for externally intercepted contaminants, W_{Crop}, a^{-1}

Element	**Pasture, root vegetables, fruit**	**Grain**	**Green vegetables**
C	500	500	500
Al, Si, Cl, Ca, Ti, Fe, Co, Ni, Se, Sr, Zr, Nb, Mo, Tc, Pd, Ag, Sn, I, Cs, Sm, Ho, Hg, Pb, Po, Ra, Ac, Th, Pa, U, Np, Pu, Am, Cm, Cf	17	17	17

5.4.5 Fraction of the intercepted contamination that is absorbed to the internal parts of the plant

Data for absorption from external surfaces and translocation to edible tissues are often combined in the literature. Tables 7 to 11 of IAEA (2010) contain data for the translocation fraction (%) for a range of elements and plant types, although the majority of the data relate to Cs and Sr. These data are also discussed in more detail in IAEA (2009), where it is noted that the scarcity of literature on this process highlights an important lack of knowledge, e.g. about how absorption and

[12] Growth dilution is included in the definition of weathering on page 45 of IAEA (2009), which forms the basis of the values presented in IAEA (2010).

translocation might change during plant growth or the effects of chronic contamination. This discussion also emphasises the lack of data for most radionuclides and the potentially inappropriate use of chemical analogues in the absence of element-specific data.

An extensive grain dataset has been reviewed in IAEA (2010). The range of absorption and translocation fractions reported for grain is between 0.001 and 0.1 for various elements, plant types and stages of plant growth, with a typical value of 0.01. The range of reported values for the other crops is similar to that of grain. The limited number of values reported for the actinides are lower, which reflects their low bioavailability, while values for lanthanides would be expected to be similar to those for the higher actinides.

The absorption fractions used are given in Tab. 5-17**.** They are only relevant for root vegetables, fruit and grain, as all external contamination remaining on green vegetables and pasture is assumed to be associated with edible tissues.

Tab. 5-17: Absorption fraction from external intercepted contamination to internal plant, f_{abs}, unitless

Footnotes discussing parameter values are included below the table.

Element	Root vegetables, fruit and grain	Green vegetables and pasture [1]	Note
C	n/a	n/a	2
Al, Si, Cl, Ca, Ti, Fe, Co, Ni, Se, Sr, Zr, Nb, Mo, Tc, Pd, Ag, Sn, I, Cs, Hg, Pb, Po, Ra, U	0.01	0	3
Sm, Ho, Ac, Th, Pa, Np, Pu, Am, Cm, Cf	0.001	0	3

Notes for Tab. 5-17:

1 All external contamination remaining on green vegetables and pasture is taken to be associated with edible tisues, so absorption and translocation fractions are irrelevant.

2 The representation of the behaviour of C-14 within the soil-plant system is supported by more detailed modelling, as summarised in Guillemot et al. (2024).

3 For most elements, absorption fractions of 0.01 are used, whereas translocation fractions of 0.001 are used for lanthanides and actinides (excluding uranium). U tends to be much more soluble in the environment than the other actinides and has biochemical similarities with Ca, so its translocation fraction is taken to be 0.01.

5.4.6 Transfer factor from feed to beef

The transfer factor (TF) from feed to beef represents the equilibrium concentration in meat given a rate of radionuclide ingestion in animal feed and has units of (Bq kg^{-1} fw) per (Bq day^{-1}). Values are primarily based on transfer factors in IAEA (2010) where data are available, and Walke et al. (2013b) where not. The values are given in Tab. 5-18.

Tab. 5-18: Transfer factor from feed to beef, K_{meat}, (Bq kg^{-1} fw) per (Bq day^{-1})

Footnotes discussing parameter values are included below the table.

Element	Value	Notes
C	8E-02	1
Al	5E-05	2
Si	2E-03	3
Cl	2E-02	4
Ca	1E-02	4
Ti	2E-03	5
Fe	1E-02	4
Co	4E-04	4
Ni	1E-02	1

Element	Value	Notes
Se	1E-01	1
Sr	1E-03	4
Zr	2E-04	6
Nb	2E-04	6
Mo	1E-03	4
Tc	8E-04	1
Pd	1E-03	1
Ag	8E-03	1
Sn	2E-03	1
I	7E-03	4
Cs	2E-02	4
Sm	1E-04	1
Ho	1E-04	1
Hg	2E+00	7
Pb	7E-04	4
Po	3E-03	1
Ra	2E-03	4
Ac	5E-05	1
Th	2E-04	4
Pa	1E-03	1
U	4E-04	4
Np	1E-04	1
Pu	1E-06	4
Am	5E-05	8
Cm	5E-05	1
Cf	5E-05	8

Notes for Tab. 5-18:

1 Table 20 of Walke et al. (2013b).

2 Al occurs only in the 3+ state and is generally poorly bioavailable. One of the 3+ higher actinides, Am, is used as an analogue.

3 Although Si is an essential trace element, it does not have a biogeochemical cycle comparable to carbon. Furthermore, the stable element data are not very helpful because of the predominance of silicates (and particularly aluminosilicates) in the environment. Partly due to the abundance of data for Sn, which has a similar chemistry as Si and forms a variety of organic complexes and is accumulated to some degree in mineralised tissues, Sn is used as the analogue.

4 Table 30 of IAEA (2010). It is noted that, as in many cases, there are some limitations in the data. For example, the value for Ra is slightly greater than that for Sr, whereas one might expect the reverse, and the value for Th may be somewhat large compared with the values for the other higher actinides (although this still indicates bioexclusion rather than bioaccumulation). These limitations likely arise due to variability in the data and/or the relatively small number of supporting studies. The IAEA (2010) values are prefered because they represent an authoritative source.

5 Ti has low bioavailability. Its only stable environmental oxidation state is 4+, and compounds like the tetrachloride hydrolyse rapidly to oxides of the element. Sn is used as an analogue.

6 Very low values are reported in Table 30 of IAEA (2010). However, these are only based on a single sample in each case. A value of 2E-4 is preferred here based on Sections 4.7 and 4.8 of Thorne (2003) and consistent with Thorne (2008) and Walke et al. (2013b).

7 The stable Hg content of soft tissues in humans is 13 mg and the rate of intake in food and fluids is 0.015 mg d^{-1} (ICRP 1980). Soft tissues in a 70-kg reference man comprise 65 kg (ICRP 1975). Therefore, the concentration in soft tissues is 0.2 mg[Hg] kg^{-1}. Hence the TF value is 0.2/0.015 = 13.3 d kg^{-1}. Note that the f_1 value for Hg is about 0.02 (ICRP 1980) and this is included in the estimated TF value. For Hg entering the systemic circulation directly (i.e. for f_1 = 1.0), the TF value would be 667 d kg^{-1}, which is in accordance with the persistent retention of Hg in the body. For other species, the biokinetics are similar, so the TF value can be scaled as 70/M, where M is the live mass of the animal of interest. The mass of a cow is assumed to be 500 kg.

8 From Table 20 of Walke et al. (2013b), which is preferred over the single value for Am in Table 30 of IAEA (2010) because (i) Am, Cm and Cf are very similar biochemically, and (ii) there is evidence that the bioavailability of Am lies between that of Pu and that of Np (see discussion in Walke et al. (2021)).

5.4.7 Transfer factor from feed to milk

The transfer factor from feed to milk represents the equilibrium concentration in milk given a rate of radionuclide ingestion in animal feed and has units of (Bq kg^{-1} fw) per (Bq day^{-1}). Howard et al. (2017) represent the most recent international compilation for radionuclide transfer to milk. The data in Howard et al. (2017) are presented as (Bq L^{-1}) per (Bq day^{-1}). However, in practice, 1 L of milk has a mass of approximately 1 kg fresh weight (Walke et al. 2021), meaning that values reported in IAEA (2010), and in other sources, are used directly here.

Tab. 5-19: Transfer factor from feed to milk, K_{milk}, (Bq kg^{-1} fw) per (Bq day^{-1})

Footnotes discussing parameter values are included below the table.

Element	Value	Notes
C	9E-03	1
Al	3E-04	2
Si	1E-03	3
Cl	2E-02	2
Ca	1E-02	2
Ti	2E-02	2
Fe	4E-05	2
Co	3E-04	2
Ni	3E-03	2

Element	Value	Notes
Se	4E-03	2
Sr	1E-03	4
Zr	4E-06	2
Nb	4E-07	2
Mo	1E-03	2
Tc	8E-04	1
Pd	1E-03	1
Ag	3E-04	1
Sn	1E-03	1
I	6E-03	4
Cs	5E-03	4
Sm	2E-05	1
Ho	2E-05	1
Hg	8E-04	2
Pb	2E-04	2
Po	2E-04	2
Ra	5E-04	2
Ac	2E-06	1
Th	1E-03	2
Pa	1E-06	1
U	3E-03	2
Np	5E-06	1
Pu	4E-05	2
Am	2E-06	2
Cm	2E-06	5
Cf	2E-06	5

Notes for Tab. 5-19:

1 Table 20 of Walke et al. (2013b).

2 Table 5a of Howard et al. (2017).

3 Although Si is an essential trace element, it does not have a biogeochemical cycle comparable to C. Furthermore, the stable element data are not very helpful, because of the predominance of silicates (and particularly aluminosilicates) in the environment. In part, due to the abundance of data for Sn, which has a similar chemistry as Si and forms a variety of organic complexes and is accumulated to some degree in mineralised tissues, Sn is used as the analogue.

4 Table 2a of Howard et al. (2017).

5 Am, Cm and Cf are very similar biochemically, so the value for Am from Table 5a of Howard et al. (2017) is adopted.

5.4.8 Transfer factor from feed to eggs

Transfer factors from feed to eggs are given in Tab. 5-20.

Tab. 5-20: Transfer factor from feed to eggs, K_{eggs}, (Bq kg^{-1} fw) per (Bq day^{-1})

Footnotes discussing parameter values are included below the table.

Element	**Value**	**Notes**
C	8.E+00	1
Al	3.E-03	2
Si	1.E-01	3
Cl	2.E+00	1
Ca	4.E-01	4
Ti	1.E-01	5
Fe	2.E+00	4
Co	3.E-02	4
Ni	1.E+00	1
Se	2.E+01	1
Sr	4.E-01	4
Zr	2.E-04	4
Nb	1.E-03	4
Mo	6.E-01	4
Tc	1.E-01	1
Pd	1.E-02	1
Ag	8.E-02	1
Sn	1.E-01	6
I	2.E+00	4
Cs	4.E-01	4
Sm	3.E-03	1
Ho	3.E-03	1
Hg	4.E-02	7
Pb	1.E+00	1
Po	4.E-01	8
Ra	4.E-02	1
Ac	5.E-03	1
Th	3.E-03	9
Pa	1.E-01	1
U	1.E+00	4

Element	Value	Notes
Np	1.E-02	1
Pu	1.E-03	4
Am	3.E-03	4
Cm	3.E-03	10
Cf	3.E-03	10

Notes for Tab. 5-20:

1 Table 20 of Walke et al. (2013b).

2 Al occurs only in the 3+ state and is generally poorly bioavailable. One of the 3+ higher actinides, Am, is used as an analogue.

3 Although Si is an essential trace element, it does not have a biogeochemical cycle comparable to C. Furthermore, the stable element data are not very helpful, because of the predominance of silicates (and particularly aluminosilicates) in the environment. In part, due to the abundance of data for Sn, which has a similar chemistry as Si and forms a variety of organic complexes and is accumulated to some degree in mineralised tissues, Sn is used as the analogue.

4 Table 35 of IAEA (2010).

5 Ti has low bioavailability. Its only stable environmental oxidation state is 4+, and compounds like the tetrachloride hydrolyse rapidly to oxides of the element. Sn is used as an analogue.

6 The biokinetics of Sn are similar across different animal species (Coughtrey et al. 1983) so allometric scaling is applied. In the absence of specific data, the value is assumed to be 50 (10 to 100) times that of meat transfer. If the transfer factor is scaled inversely with the mass of the animal (i.e. the retention function is the same across species), then the transfer factor would be a factor of 500 kg:3 kg = 167 larger. However, in practice, retention is generally lower in smaller animals. Allometric arguments based on metabolisable energy requirements suggest a ratio of masses to the power 0.75 (Lawrence & Fowler 2002) giving a scale factor of 46 rather than 167.

7 Table G.3 of CSA (2014).

8 Table 35 of IAEA (2010) gives a value of 3.1 day kg^{-1} based on a single source. Po is quite well absorbed in the gastrointestinal tract and uniformly distributed in soft tissues (Walke et al. 2021). However, a value of 3.1 day kg^{-1} reported in Table 35 of IAEA (2010) is based on only one measurement and is probably excessive. The value would not be expected to exceed that for Cs, which is also well absorbed and uniformly distributed in soft tissues. Therefore a value of 0.4 day kg^{-1} is used by analogy with Cs.

9 A value of 3E-3 day kg^{-1} is used here, based on the discussion in Section 2.17.3 of Thorne (2008). It is noted that Walke et al. (2013b) and Thorne & Walke (2020) use a value of 3E-2 day kg^{-1} based on biokinetic modelling and a safety factor of ten. However, a value of 3E-3 day kg^{-1} is consistent with the values for Pu, Am and Cm.

10 Am, Cm and Cf are very similar biochemically, so the value for Am from Table 35 of IAEA (2010) is adopted.

5.4.9 Transfer factor from feed to chicken meat

The transfer factor from feed to chicken meat represents the equilibrium concentration in meat given a rate of radionuclide ingestion in animal feed and has units of (Bq/kg fw) per (Bq/day). Values are primarily based on transfer factors to beef in IAEA (2010) where data are available, and Walke et al. (2013b) where not. The values are given in Tab. 5-21.

Tab. 5-21: Transfer factor from feed to chicken meat, K_{meat}, (Bq kg^{-1} fw) per (Bq day^{-1})

Footnotes discussing parameter values are included below the table.

Element	Value	Notes
C	8E+0	1
Al	5E-3	2
Si	1E-1	3
Cl	2E+0	1
Ca	4E-2	4
Ti	1E-1	3
Fe	2E+0	5
Co	1E-1	6
Ni	1E+0	1
Se	1E+0	4
Sr	2E-2	4
Zr	2E-4	5
Nb	3E-4	4
Mo	2E-1	4
Tc	1E-1	1
Pd	1E-2	1
Ag	8E-2	1
Sn	1E-1	5
I	1E-1	1
Cs	3E+0	4
Sm	3E-3	1
Ho	3E-3	1
Hg	4E-2	5
Pb	1E+0	1
Po	2E+0	4
Ra	4E-2	1
Ac	5E-3	1
Th	3E-2	1
Pa	1E-1	1

Element	Value	Notes
U	1E+0	1
Np	1E-2	1
Pu	1E-3	1
Am	5E-3	1
Cm	5E-3	1
Cf	5E-3	2

Notes for Tab. 5-21:

1 Table 20 of Walke et al. (2013b).

2 Am is used as an analogue for Al.

3 Sn is used as an analogue for Si and Ti.

4 Table 34 of IAEA (2010).

5 Consistent with the value for transfer to eggs.

6 Based on consideration of values for chicken meat and eggs in IAEA (2010).

5.4.10 Transfer factor from surface water to fish

The transfer factor from surface water to fish represents the equilibrium concentration in edible fish tissues for a given radionuclide concentration in filtered freshwater. Data for this parameter are presented in units of (Bq kg^{-1} fw) per (Bq m^{-3}). The parameter values are given in Tab. 5-22. Unless otherwise stated, the data are the geometric mean data for fish muscle presented in Table 57 of IAEA (2010).

Neither IAEA (2010) nor the supporting IAEA (2009) discuss whether the transfer factors relate to filtered or unfiltered water. Good experimental protocols use filtered water, however, this is not always the case, and the degree of filtration will vary between studies. The IAEA (2010) values are preferentially adopted in Tab. 5-22, based on the assumption that the review excluded studies that did not adopt good experimental protocols and that the data can therefore be taken to represent transfer factors relating to filtered water.

Tab. 5-22: Transfer factor from surface water to fish, K_{ff}, (Bq kg^{-1} fw) per (Bq m^{-3})

Footnotes discussing parameter values are included below the table.

Element	Value	Notes
C	4.E+02	1
Al	5.E-02	1
Si	3.E+00	2
Cl	5.E-02	1
Ca	1.E-02	1
Ti	2.E-01	1
Fe	2.E-01	1
Co	8.E-02	1

Element	Value	Notes
Ni	2.E-02	1
Se	6.E+00	1
Sr	3.E-03	1
Zr	2.E-02	1
Nb	2.E-02	3
Mo	2.E-03	1
Tc	3.E-02	4
Pd	1.E-01	4
Ag	1.E-01	1
Sn	3.E+00	4
I	3.E-02	1
Cs	3.E+00	1
Sm	1.E-01	5
Ho	1.E-01	5
Hg	6.E+00	1
Pb	3.E-02	1
Po	4.E-02	1
Ra	4.E-03	1
Ac	2.E-01	6
Th	6.E-03	1
Pa	2.E-01	6
U	1.E-03	1
Np	3.E-02	4
Pu	3.E-02	4
Am	2.E-01	1
Cm	2.E-01	6
Cf	2.E-01	6

Notes for Tab. 5-22:

1 Table 57 of IAEA (2010).

2 Although Si is an essential trace element, it does not have a biogeochemical cycle comparable to C. Furthermore, the stable element data are not very helpful because of the predominance of silicates (and particularly aluminosilicates) in the environment. Partly due to the abundance of data for Sn, which has a similar chemistry as Si and forms a variety of organic complexes and is accumulated to some degree in mineralised tissues, Sn is used as the analogue.

3 Based on analogy with Zr.

4 Table 44 of Walke et al. (2013b).

5 Based on analogy with Eu, with data for Eu from Table 57 of IAEA (2010).

6 Based on analogy with Am.

5.5 Radionuclide-dependent data

Radionuclide half-lives, modelled decay chains and assumptions with regard to radionuclides treated in secular equilibrium with their parents are described in Section 5.5.1. Ingestion dose coefficients are then presented in Section 5.5.2, inhalation dose coefficients in Section 5.5.3 and dose coefficients for external irradiation in Section 5.5.4.

5.5.1 Radionuclides and decay-chain characteristics

Radionuclides screened for inclusion in post-closure biosphere modelling for SGT-E3 and RBG assessments are listed in Tab. 5-23.

The nuclear data used in Nagra's MIRAM-RBG database (Nagra 2023), as well as the waste characterisation simulations, are based on the ENDF/B-VII.1 nuclear data library (Chadwick et al. 2011). For the sake of consistency, the decay characteristics considered in this work are also based on ENDF/B-VII.1. It is noted that there are some differences between the ENDF/B-VII.1 library and the decay characteristics used by the ICRP in its derivation of dose coefficients (ICRP 2009); for reference purposes, the ICRP values are also shown in Tab. 5-23.

Tab. 5-23: Half-lives for radionuclides requiring explicit modelling in the biosphere

Biosphere modelling uses half-lives and decay characteristics based on the ENDF/B-VII.1 library (Chadwick et al. 2011). Half-lives from (ICRP 2009) are included for reference with differences highlighted by an asterisk (*).

Radionuclide	**Half-life**		**Radionuclide**	**Half-life**	
	ENDF/B-VII.1	**ICRP (2009)**		**ENDF/B-VII.1**	**ICRP (2009)**
Ac-227	21.772 y	21.772 y	Pb-202	5.25E+4 y	5.25E+4 y
Ag-108m*	438 y	418 y	Pb-205*	1.73E+7 y	1.53E+7 y
Al-26	7.17E+5 y	7.17E+5 y	Pb-210	22.2 y	22.2 y
Am-241	432.2 y	432.2 y	Pd-107	6.5E+6 y	6.5E+6 y
Am-242m	141 y	141 y	Po-209	102 y	102 y
Am-243	7.37E+3 y	7.37E+3 y	Po-210	138.376 d	138.376 d
C-14	5.70E+3 y	5.70E+3 y	Pu-238	87.7 y	87.7 y
Ca-41	1.02E+5 y	1.02E+5 y	Pu-239	2.411E+4 y	2.411E+4 y
Cf-249	351 y	351 y	Pu-240*	6561 y	6564 y
Cf-251	898 y	900 y	Pu-241*	14.29 y	14.35 y
Cl-36	3.01E+5 y	3.01E+5 y	Pu-242*	3.74E+5 y	3.75E+5 y
Cm-242*	162.9 d	162.8 d	Pu-244*	8.11E+7 y	8.0E+7 y
Cm-243	29.1 y	29.1 y	Ra-226	1.60E+3 y	1.60E+3 y
Cm-244	18.11 y	18.0 y	Ra-228	5.75 y	5.75 y
Cm-245	8.5E+3 y	8.5E+3 y	Se-79	2.95E+5 y	2.95E+5 y
Cm-246	4.76E+3 y	4.76E+3 y	Si-32*	153 y	132 y
Cm-247	1.56E+7 y	1.56E+7 y	Sm-151	90 y	90 y

Radionuclide	Half-life	
	ENDF/B-VII.1	ICRP (2009)
Cm-248	3.48E+5 y	3.48E+5 y
Co-60	5.2713 y	5.2713 y
Cs-135	2.3E+6 y	2.3E+6 y
Cs-137*	30.08 y	30.1671 y
Fe-60	1.5E+6 y	1.5E+6 y
Hg-194*	444 y	440 y
Ho-166m	1.20E+3 y	1.20E+3 y
I-129	1.57E+7 y	1.57E+7 y
Mo-93	4.0E+3 y	4.0E+3 y
Nb-91	680 y	680 y
Nb-93m	16.13 y	16.13 y
Nb-94	2.03E+4 y	2.03E+4 y
Ni-59*	7.6E+4 y	1.01E+5 y
Ni-63*	101.2 y	100.1 y
Np-237	2.144E+6 y	2.144E+6 y
Pa-231	3.276E+4 y	3.276E+4 y

Radionuclide	Half-life	
	ENDF/B-VII.1	ICRP (2009)
Sn-121m	43.9 y	43.9 y
Sn-126	2.3E+5 y	2.3E+5 y
Sr-90	28.79 y	28.79 y
Tc-99	2.111E+5 y	2.111E+5 y
Th-228*	1.9120 y	1.9116 y
Th-229	7.34E+3 y	7.34E+3 y
Th-230	7.538E+4 y	7.538E+4 y
Th-232	1.405E+10 y	1.405E+10 y
Ti-44	60.0 y	60.0 y
U-232	68.9 y	68.9 y
U-233	1.592E+5 y	1.592E+5 y
U-234	2.455E+5 y	2.455E+5 y
U-235	7.04E+8 y	7.04E+8 y
U-236	2.342E+7 y	2.342E+7 y
U-238	4.468E+9 y	4.468E+9 y
Zr-93	1.53e+6 y	1.53e+6 y

Radionuclides with half-lives greater than about 60 days are explicitly represented in post-closure biosphere modelling. The major decay chains are illustrated in Fig. 5-1, below.

4n chain:		Cm-248 →	Pu-244 →	Pu-240 →	U-236 →	Th-232 →	Ra-228 →	Th-228	
		Cm-244 →	Pu-240 →	U-236 →	Th-232 →	Ra-228 →	Th-228		
						U-232 →	Th-228		
4n+2 chain:		Cm-246 →	Pu-242 →	U-238 →	U-234 →	Th-230 →	Ra-226 →	Pb-210 →	Po-210
			Cm-242 →	Pu-238 →	U-234 →	Th-230 →	Ra-226 →	Pb-210 →	Po-210
	Am-242m →	0.8232 →	Cm-242 →	Pu-238 →	U-234 →	Th-230 →	Ra-226 →	Pb-210 →	Po-210
		0.1722 →	Pu-242 →	U-238 →	U-234 →	Th-230 →	Ra-226 →	Pb-210 →	Po-210
		0.0046 →		Pu-238 →	U-234 →	Th-230 →	Ra-226 →	Pb-210 →	Po-210
4n+1 chain:		Cf-249 →	Cm-245 →	Pu-241 →	Am-241 →	Np-237 →	U-233 →	Th-229	
4n+3 chain:		Cf-251 →	Cm-247 →	Pu-243 →	Am-243 →	Pu-239 →	U-235 →	Pa-231 →	Ac-227
			Cm-243 →	0.0029 →	Am-243 →	Pu-239 →	U-235 →	Pa-231 →	Ac-227
				0.9971 →		Pu-239 →	U-235 →	Pa-231 →	Ac-227

Fig. 5-1: Explicitly modelled radionuclides in the major decay series, with branching ratios based on ENDF/B-VII.1

Shorter explicitly modelled decay chains are given below, with branching ratios based on ENDF/B-VII.1:

- Fe-60 → Co-60 (0.9976)
- Mo-93 → Nb-93m (0.88)
- Zr-93 → Nb-93m (0.975)
- Po-209 → Pb-205 (0.9952)

In compiling dose coefficients, it is important to include the contribution from short-lived progeny. Short-lived progeny represent radioisotopes with half-lives that are short compared to biosphere transfer processes. In this way, they can be assumed to be present in secular equilibrium with parent radionuclides that have longer half-lives. For every Becquerel of the explicitly modelled parent, the short-lived progeny are taken to be present consistent with any associated branching ratios.

The following radionuclides listed in Tab. 5-23 include a single short-lived daughter (if a branching ratio is applicable, it is listed in brackets):

- Ag-108m → Ag-108 (0.087)
- Am-243 → Np-239
- Cm-247 → Pu-243
- Cs-137 → Ba-137m (0.947)
- Fe-60 → Co-60m
- Hg-194 → Au-194
- Np-237 → Pa-233
- Pb-202 → Tl-202
- Ra-228 → Ac-228
- Si-32 → P-32
- Sn-121m → Sn-121 (0.776)
- Sr-90 → Y-90
- Ti-44 → Sc-44
- U-235 → Th-231

For those radionuclides with longer decay chains, details of the decay chains and branching ratios are given in the tables below, based on ENDF/B-VII.1.

Tab. 5-24: Short-lived progeny and branching ratios for Ac-227 (ENDF/B-VII.1)

f indicates branching fractions.

Nuclide	Half-life	Daughter products and branching fractions			
		f_1	Nuclide	f_2	Nuclide
Ac-227	21.772 y	9.862E-01	Th-227	1.380E-02	Fr-223
Th-227	18.68 d	1.000E+00	Ra-223		
Fr-223	22.00 m	9.999E-01	Ra-223	6.000E-05	At-219
Ra-223	11.43 d	1.000E+00	Rn-219		
At-219	56 s	9.700E-01	Bi-215	3.000E-02	Rn-219
Rn-219	3.96 s	1.000E+00	Po-215		
Bi-215	7.7 m	1.000E+00	Po-215		
Po-215	1.781E-3 s	1.000E+00	Pb-211	2.300E-06	At-215
Pb-211	36.1 m	1.000E+00	Bi-211		
At-215	1E-4 s	1.000E+00	Bi-211		
Bi-211	2.14 m	9.972E-01	Tl-207	2.760E-03	Po-211
Tl-207	4.77 m	1.000E+00	Pb-207 (stable)		
Po-211	0.516 s	1.000E+00	Pb-207 (stable)		

Tab. 5-25: Short-lived progeny and branching ratios for Am-242m (ENDF/B-VII.1)

f indicates branching fractions. SF is spontaneous fission.

Note that the table is curtailed at Pu-238, Pu-242 and Cm-242 because they have sufficiently long half-lives to be explicitly modelled.

Nuclide	Half-life	Daughter products and branching fractions			
		f_1	Nuclide	f_2	Nuclide
Am-242m	141 y	9.954E-01	Am-242	4.590E-03	Np-238
Am-242	16.02 h	8.270E-01	Cm-242	1.730E-01	Pu-242
Np-238	2.117 d	1.000E+00	Pu-238		
Cm-242	162.9 d	1.000E+00	Pu-238	6.100E-08	SF
Pu-242	3.74E+5 y	1.000E+00	U-238	5.500E-06	SF
Pu-238	87.7 y	1.000E+00	U-234	1.860E-09	SF

Tab. 5-26: Short-lived progeny and branching ratios for Po-210 (ENDF/B-VII.1)

Note that Po-210 has a sufficiently long half-life to be explicitly modelled. *f* indicates branching fractions.

Nuclide	Half-life	Daughter products and branching fractions			
		f_1	Nuclide	f_2	Nuclide
Pb-210	22.20 y	1.000E+00	Bi-210	1.900E-08	Hg-206
Bi-210	5.012 d	1.000E+00	Po-210	1.320E-06	Tl-206
Hg-206	8.32 m	1.000E+00	Tl-206		
Po-210	138.376 d	1.000E+00	Pb-206 (stable)		
Tl-206	4.202 m	1.000E+00	Pb-206 (stable)		

Tab. 5-27: Short-lived progeny and branching ratios for Pu-244 (ENDF/B-VII.1)

Note that Pu-240 has a sufficiently long half-life to be explicitly modelled. *f* indicates branching fractions. SF is spontaneous fission.

Nuclide	Half-life	Daughter products and branching fractions			
		f_1	Nuclide	f_2	Nuclide
Pu-244	8.11E+7 y	9.988E-01	U-240	1.250E-03	SF
U-240	14.1 h	1.000E+00	Np-240m		
Np-240m	7.22 m	1.200E-03	Np-240	9.988E-01	Pu-240
Np-240	61.9 m	1.000E+00	Pu-240		
Pu-240	6561 y	1.000E+00	U-236	5.700E-08	SF

Tab. 5-28: Short-lived progeny and branching ratios for Ra-226 (ENDF/B-VII.1)

Note that the table is curtailed at Pb-210, which has a sufficiently long half-life to be explicitly modelled. *f* indicates branching fractions.

Nuclide	Half-life	Daughter products and branching fractions			
		f_1	Nuclide	f_2	Nuclide
Ra-226	1600 y	1.000E+00	Rn-222		
Rn-222	3.8235 d	1.000E+00	Po-218		
Po-218	3.098 m	9.998E-01	Pb-214	2.000E-04	At-218
Pb-214	26.8 m	1.000E+00	Bi-214		
At-218	1.5 s	9.990E-01	Bi-214	1.000E-03	Rn-218
Bi-214	19.9 m	9.998E-01	Po-214	2.100E-04	Tl-210
Rn-218	3.5E-2 s	1.000E+00	Po-214		
Po-214	1.643E-4 s	1.000E+00	Pb-210		
Tl-210	1.30 m	9.999E-01	Pb-210	8.500E-05	Pb-209
Pb-210	22.20 y	1.000E+00	Bi-210	1.900E-08	Hg-206
Pb-209	3.253 h	1.000E+00	Bi-209 (stable)		

Tab. 5-29: Short-lived progeny and branching ratios for Sn-126 (ENDF/B-VII.1)

f indicates branching fractions.

Nuclide	Half-life	Daughter products and branching fractions			
		f_1	Nuclide	f_2	Nuclide
Sn-126	2.30E+5 y	6.700E-01	Sb-126n	3.300E-01	Sb-126m
Sb-126n	11 s	1.000E+00	Sb-126m		
Sb-126m	19.15 m	1.400E-01	Sb-126	8.600E-01	Te-126 (stable)
Sb-126	12.35 d	1.000E+00	Te-126 (stable)		

Tab. 5-30: Short-lived progeny and branching ratios for Th-228 (ENDF/B-VII.1)
f indicates branching fractions.

Nuclide	**Half-life**	**Daughter products and branching fractions**			
		f_1	**Nuclide**	f_2	**Nuclide**
Th-228	1.912 y	1.000E+00	Ra-224		
Ra-224	3.66 d	1.000E+00	Rn-220		
Rn-220	55.6 s	1.000E+00	Po-216		
Po-216	0.145 s	1.000E+00	Pb-212		
Pb-212	10.64 h	1.000E+00	Bi-212		
Bi-212	60.55 m	6.406E-01	Po-212	3.594E-01	Tl-208
Po-212	2.99E-7 s	1.000E+00	Pb-208 (stable)		
Tl-208	3.053 m	1.000E+00	Pb-208 (stable)		

Tab. 5-31: Short-lived progeny and branching ratios for Th-229 (ENDF/B-VII.1)

f indicates branching fractions.

Nuclide	Half-life	Daughter products and branching fractions			
		f_1	Nuclide	f_2	Nuclide
Th-229	7.34E+3 y	1.000E+00	Ra-225		
Ra-225	14.9 d	1.000E+00	Ac-225		
Ac-225	10.0 d	1.000E+00	Fr-221		
Fr-221	4.9 m	1.000E+00	At-217		
At-217	3.23E-2 s	9.999E-01	Bi-213	7.000E-05	Rn-217
Bi-213	45.59 m	9.780E-01	Po-213	2.200E-02	Tl-209
Rn-217	5.4E-4 s	1.000E+00	Po-213		
Po-213	4.2E-6 s	1.000E+00	Pb-209		
Tl-209	2.2 m	1.000E+00	Pb-209		
Pb-209	3.253 h	1.000E+00	Bi-209 (stable)		

Tab. 5-32: Short-lived progeny and branching ratios for U-238 (ENDF/B-VII.1)

Note that the table is curtailed at U-234 and Th-230, which have sufficiently long half-lives to be explicitly modelled. *f* indicates branching fractions. SF is spontaneous fission.

Nuclide	Half-life	Daughter products and branching fractions			
		f_1	Nuclide	f_2	Nuclide
U-238	4.468E+9 y	1.000E+00	Th-234	5.460E-07	SF
Th-234	24.10 d	1.000E+00	Pa-234m		
Pa-234m	1.159 m	1.600E-03	Pa-234	9.984E-01	U-234
Pa-234	6.70 h	1.000E+00	U-234		
U-234	2.455E+5 y	1.000E+00	Th-230	2.000E-11	SF

5.5.2 Ingestion dose coefficients

The data for adult ingestion dose coefficients are given in Tab. 5-33.

At the time of preparation of this report, the ICRP is consulting on an update to its compendium of dose coefficients. That consultation takes account of updated recommendations for tissue weighting factors from ICRP Publication 103 (ICRP 2007) as well as other changes, including updated biokinetic modelling. Notable changes in the consultation document include reductions in the recommended ingestion dose coefficients for C-14, Mo-93, Tc-99, and Ra-226.

The ingestion dose coefficients included in the Swiss Radiological Protection Ordinance (RPO) (SFC 2021) are based on ICRP recommendations, so changes can be expected to be reflected in the Swiss RPO in due course. However, given that the new ICRP recommendations are not yet finalised, the assessment here is based on the earlier recommendations and values encoded in the current version of the Swiss RPO.

Tab. 5-33: Committed effective dose coefficients for ingestion, H_{ing}, Sv Bq^{-1}

Values are preferentially based on Table 2 of Annex 5 of the Swiss RPO (SFC 2021), and Annex F of ICRP Publication 119 (ICRP 2012). Neither the Swiss RPO nor ICRP Publication 119 include ingestion dose coefficients for Nb-91 or Po-209. Values for these radionuclides were drawn from the previous Nagra compilation. Where appropriate, these values account for short-lived progeny as described in Section 5.5.1.

Radionuclide	**Ingestion dose coefficients, Sv Bq^{-1}**
Ac-227	1.21E-06
Ag-108m	2.30E-09
Al-26	3.50E-09
Am-241	2.00E-07
Am-242m	1.90E-07
Am-243	2.01E-07
C-14	5.80E-10
Ca-41	1.90E-10
Cf-249	3.50E-07
Cf-251	3.60E-07
Cl-36	9.30E-10
Cm-242	1.20E-08
Cm-243	1.50E-07
Cm-244	1.20E-07
Cm-245	2.10E-07
Cm-246	2.10E-07
Cm-247	1.90E-07
Cm-248	7.70E-07
Co-60	3.40E-09
Cs-135	2.00E-09
Cs-137	1.30E-08
Fe-60	1.10E-07
Hg-194	2.14E-08
Ho-166m	2.00E-09
I-129	1.10E-07
Mo-93	3.10E-09
Nb-91	4.70E-11
Nb-93m	1.20E-10
Nb-94	1.70E-09
Ni-59	6.30E-11
Ni-63	1.50E-10

Radionuclide	Ingestion dose coefficients, Sv Bq^{-1}
Np-237	1.11E-07
Pa-231	7.10E-07
Pb-202	9.25E-09
Pb-205	2.80E-10
Pb-210	6.91E-07
Pd-107	3.70E-11
Po-209	5.40E-07
Po-210	1.20E-06
Pu-238	2.30E-07
Pu-239	2.50E-07
Pu-240	2.50E-07
Pu-241	4.80E-09
Pu-242	2.40E-07
Pu-244	2.41E-07
Ra-226	2.80E-07
Ra-228	6.90E-07
Se-79	2.90E-09
Si-32	2.96E-09
Sm-151	9.80E-11
Sn-121m	5.58E-10
Sn-126	5.07E-09
Sr-90	3.07E-08
Tc-99	6.40E-10
Th-228	1.43E-07
Th-229	6.13E-07
Th-230	2.10E-07
Th-232	2.30E-07
Ti-44	6.15E-09
U-232	3.30E-07
U-233	5.10E-08
U-234	4.90E-08
U-235	4.73E-08
U-236	4.70E-08
U-238	4.84E-08
Zr-93	1.10E-09

5.5.3 Inhalation dose coefficients

Adult inhalation dose coefficients for particulate aerosols are available in the Swiss RPO (SFC 2021). Inhalation dose coefficients for particulate aerosols with an AMAD of 1 µm[13] are typically available for different rates of absorption from the lungs into the blood, reflecting the solubility of particulate materials deposited in the respiratory tract. Values can be available for fast (F), moderate (M), and slow (S) rates of absorption.

The Swiss RPO (SFC 2021) specifies the inhalation category type that is associated with recommended inhalation dose coefficients for each radionuclide. These recommendations are consistent with Table 2 of ICRP Publication 72 (ICRP 1996).

The following order of precedence has been adopted with regard to inhalation type:

- where the radionuclide is included in the Swiss RPO, the inhalation dose coefficient and associated inhalation type are used from that source;
- where the element has a radioisotope that is included in the Swiss RPO, an inhalation type is adopted that is consistent with the Swiss RPO;
- the inhalation type is drawn from recommendations in Table 2 of ICRP Publication 72 (ICRP 1996), consistent with the approach adopted in the Swiss RPO;
- where no recommendations for inhalation types are available, the highest inhalation dose coefficient is adopted from the range available in ICRP Publication 119 (ICRP 2012).

The resulting inhalation dose coefficients are given in Tab. 5-34.

For C-14, the value given in Tab. 5-34 reflects that for inhalation of particulates. The value given in the Swiss RPO for C-14 is for vapour, so the particulate value from ICRP Publication 119 (ICRP 2012) is preferentially used for the recommended moderate rate of absorption for C given in ICRP Publication 72 (ICRP 1996).

For C-14 released to the atmosphere as gas, adult inhalation dose coefficients for $^{14}CO_2$ and $^{14}CH_4$ are given in Annex H of ICRP Publication 119 (ICRP 2012):

- C-14 inhaled as $^{14}CO_2$: 6.2E-12 Sv Bq^{-1}; and
- C-14 inhaled as $^{14}CH_4$: 2.9E-19 Sv Bq^{-1}.

It is reasonable to assume that any $^{14}CH_4$ reaching the topsoil is effectively completely oxidised to $^{14}CO_2$ (Guillemot et al. 2024), so the inhalation dose coefficient for $^{14}CO_2$ is used in evaluating potential inhalation doses associated with C-14 release from the soil as gas.

As with the ingestion dose coefficients given in Section 5.5.2, it is noted that, at the time of preparation of this report, the ICRP is consulting on an update to its compendium of dose coefficients. That update includes updated recommendations for inhalation dose coefficients for particulates and for gases. However, given that the new ICRP recommendations are not yet finalised, the assessment here is based on recommendations and values encoded in the current version of the Swiss RPO.

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[13] Inhalable particles representative of resuspended material (dust) from the topsoil.

Tab. 5-34: Committed effective dose coefficients for particulate inhalation, H_{inh}, Sv Bq^{-1}

Values preferentially based on Table 1 of Annex 5 of the Swiss RPO (SFC 2021) and Annex G of ICRP Publication 119 (ICRP 2012). Neither the Swiss RPO nor ICRP Publication 119 include inhalation dose coefficients for Nb-91 or Po-209. Values for these radionuclides were drawn from the previous Nagra compilation. Where appropriate, these values account for short-lived progeny as described in Section 5.5.1.

Radionuclide	**Inhalation dose coefficient, Sv Bq^{-1}**
Ac-227	5.67E-04
Ag-108m	7.40E-09
Al-26	2.00E-08
Am-241	4.20E-05
Am-242m	3.70E-05
Am-243	4.10E-05
C-14	2.00E-09
Ca-41	9.50E-11
Cf-249	7.00E-05
Cf-251	7.10E-05
Cl-36	7.30E-09
Cm-242	5.20E-06
Cm-243	3.10E-05
Cm-244	2.70E-05
Cm-245	4.20E-05
Cm-246	4.20E-05
Cm-247	3.90E-05
Cm-248	1.50E-04
Co-60	1.00E-08
Cs-135	6.90E-10
Cs-137	4.60E-09
Fe-60	1.40E-07
Hg-194	1.32E-08
Ho-166m	1.20E-07
I-129	3.60E-08
Mo-93	5.90E-10
Nb-91	3.90E-09
Nb-93m	5.10E-10

Radionuclide	**Inhalation dose coefficient, Sv Bq^{-1}**
Nb-94	1.10E-08
Ni-59	1.30E-10
Ni-63	4.80E-10
Np-237	2.30E-05
Pa-231	1.40E-04
Pb-202	6.49E-09
Pb-205	2.50E-10
Pb-210	1.19E-06
Pd-107	5.90E-10
Po-209	2.80E-06
Po-210	3.30E-06
Pu-238	4.60E-05
Pu-239	5.00E-05
Pu-240	5.00E-05
Pu-241	9.00E-07
Pu-242	4.80E-05
Pu-244	4.70E-05
Ra-226	3.53E-06
Ra-228	2.63E-06
Se-79	1.10E-09
Si-32	1.13E-07
Sm-151	4.00E-09
Sn-121m	4.68E-09
Sn-126	2.84E-08
Sr-90	3.74E-08
Tc-99	4.00E-09
Th-228	4.32E-05
Th-229	8.58E-05
Th-230	1.40E-05
Th-232	2.50E-05
Ti-44	1.20E-07
U-232	7.80E-06

Radionuclide	Inhalation dose coefficient, Sv Bq^{-1}
U-233	3.60E-06
U-234	3.50E-06
U-235	3.10E-06
U-236	3.20E-06
U-238	2.91E-06
Zr-93	1.00E-08

5.5.4 Dose coefficients for external irradiation

Dose coefficients for external irradiation, G, are drawn from US EPA guidance. The latest US EPA recommendations are reflected in Federal Guidance Report (FGR) 15 (EPA 2019). The values used represent those for soil contaminated to an infinite depth; due to the shielding effect of the soil, the dose is effectively dominated by contamination in the top 10 – 15 cm. This assumes a semi-infinite plane and uniform contamination.

The dose coefficients used for external irradiation are given in Tab. 5-35.

Tab. 5-35: Dose coefficients due to external irradiation from soil contaminated to an infinite depth (Sv a^{-1}) per (Bq m^{-3})

Values based on Table 4-5 of (EPA 2019). Where appropriate, these values account for short-lived progeny as described in Section 5.5.1.

Radionuclide	External dose coefficient, (Sv a^{-1}) per (Bq m^{-3})
Ac-227	4.02E-10
Ag-108m	1.51E-09
Al-26	2.81E-09
Am-241	6.94E-12
Am-242m	1.74E-11
Am-243	1.50E-10
C-14	9.91E-13
Ca-41	0.00E+00
Cf-249	2.81E-10
Cf-251	7.89E-11
Cl-36	1.33E-11
Cm-242	1.87E-14
Cm-243	9.09E-11

Radionuclide	External dose coefficient, (Sv a^{-1}) per (Bq m^{-3})
Cm-244	3.16E-14
Cm-245	6.12E-11
Cm-246	3.94E-12
Cm-247	2.94E-10
Cm-248	1.44E-09
Co-60	2.60E-09
Cs-135	2.65E-12
Cs-137	5.43E-10
Fe-60	5.45E-12
Hg-194	1.01E-09
Ho-166m	1.51E-09
I-129	2.49E-12
Mo-93	5.36E-14
Nb-91	1.52E-12
Nb-93m	9.59E-15
Nb-94	1.52E-09
Ni-59	1.43E-14
Ni-63	1.29E-13
Np-237	1.84E-10
Pa-231	2.68E-11
Pb-202	3.84E-10
Pb-205	1.17E-15
Pb-210	2.21E-11
Pd-107	2.15E-14
Po-209	5.59E-12
Po-210	9.47E-15
Pu-238	1.67E-14
Pu-239	4.64E-14
Pu-240	1.72E-14
Pu-241	2.37E-15
Pu-242	9.72E-14
Pu-244	3.75E-10

Radionuclide	External dose coefficient, (Sv a^{-1}) per (Bq m^{-3})
Ra-226	1.81E-09
Ra-228	8.71E-10
Se-79	1.10E-12
Si-32	4.88E-11
Sm-151	1.75E-13
Sn-121m	4.24E-12
Sn-126	1.89E-09
Sr-90	7.97E-11
Tc-99	3.19E-12
Th-228	1.60E-09
Th-229	2.82E-10
Th-230	1.96E-13
Th-232	8.65E-14
Ti-44	2.18E-09
U-232	1.25E-13
U-233	1.56E-13
U-234	5.93E-14
U-235	1.27E-10
U-236	2.94E-14
U-238	8.27E-11
Zr-93	1.53E-13

6 Model application and results

Implementation of the biosphere models and data presented in the preceding chapters is summarised in Section 6.1. The BDCFs for the reference biosphere and alternative calculation cases are provided in Section 6.2, which also reviews the contribution of the different potential exposure pathways to the reference BDCFs. Section 6.3 then presents results from deterministic and probabilistic sensitivity analyses.

6.1 Implementation in the SwiBAC code

The biosphere models presented in Chapter 4 are implemented in a software application referred to as the Swiss Biosphere Assessment Code (SwiBAC).

SwiBAC provides users with the capability to set up and run calculations for the reference biosphere model and alternative cases via text-based input files. The code uses the generic compartment-based contaminant assessment code AMBER (Quintessa 2023) as a calculation "engine". Users set up calculations by defining the structure of the model and associated data via text-based input files. SwiBAC then combines the input with a "template" that encodes the modelling approach described in the preceding chapters to generate complete AMBER case files. The SwiBAC code then runs the AMBER calculation and extracts the requested results to text-based output files. The underlying case files associated with any calculation can be explored via the AMBER code, which allows full exploration of the underlying calculations and intermediate results.

Much of the general data provided in Chapter 5 are available alongside SwiBAC as "library files" that can be called from the SwiBAC input files and/or specific values replaced/overwritten, as required.

The AMBER code is a well-established commercially available application with over 100 licensees worldwide. The code is developed and maintained within an accredited quality assurance framework that required software development standards. AMBER releases are subject to rigorous verification testing to ensure that the code performs as specified.

SwiBAC was developed under the same quality and software assurance framework as the AMBER code and complies with Nagra's software development and modelling standards. SwiBAC was originally developed and benchmarked against the preceding TAME code (Klos et al. 1996).

SwiBAC 2.0 was used for the BDCF calculations reported in Section 6.2. The specifications for those calculations have been independently checked, and the calculations were also repeated in standalone AMBER calculations that independently implement developments in SwiBAC since the introduction of SwiBAC 1.2 (Walke & Keesmann 2013), which was used in the calculations supporting SGT-E2 (Nagra 2014).

Nagra's biosphere modelling includes water and mass balance models as a foundation for the contaminant transport modelling (see Section 4.2.1). These mass-balance models are encoded within SwiBAC and do not allow a calculation to proceed if a water or mass balance is not maintained.

Another aspect of SwiBAC that helps build confidence in its application is that the code requires units to be declared for input data and will not allow a calculation if there are any inconsistencies in the units used in the calculation.

The text-based input style for SwiBAC allows for transparent usage of the code and, simplifies e.g. the identification of differences in inputs for variant calculations, etc. The style of input is also consistent with Nagra's STMAN code used for modelling the near-field (Robinson 2022) and Nagra's PICNIC-TD code used for modelling the geosphere (Robinson & Chittenden 2022).

6.2 Biosphere dose conversion factors (BDCFs)

The calculated BDCFs for the reference biosphere case are presented in Tab. 6-1, along with the time required to reach 90% of the equilibrium value for each radionuclide. There is considerable variability in the BDCFs, reflecting different half-lives, degrees of mobility/bioavailability and different degrees of radiosensitivity. The time to equilibrium also varies significantly, from 1.3 years (Po-210) to 450,000 years (Pu-244), with short-lived non-sorbing radionuclides reaching equilibrium quickly and long-lived strongly-sorbing radionuclides (and those with long-lived strongly sorbing progeny) taking much longer to reach equilibrium values. The extremely long timescale for some radionuclides to approach the BDCFs reflects the constant non-evolving nature of the stylised reference biosphere system. In practice, equilibrium would not be achieved for these radionuclides because the surface environment would be subject to change. Alternative cases below explore the effects of different biosphere conditions that could potentially result from change.

Fig. 6-1 shows the contributions of each exposure pathway to the reference BDCFs for each radionuclide. The figure illustrates the notable differences in the contributions of the exposure pathways across the range of radionuclides. The differences reflect the characteristics of each radionuclide, including the differing degrees of sorption/retention, bioavailability and relative radiotoxicity between the exposure pathways.

- In general, for most radionuclides, the largest contribution to a potential dose results from the ingestion of milk and/or grain (cereals).
- Some radionuclides have a relatively high external dose coefficient (e.g. Ag-108m, Nb-94). As a result, their BDCF is dominated by external irradiation from soil.
- For Ca-41, Cl-36 and I-129, ingestion of milk accounts for 80 – 90% of the total BDCF.
- For Se-79, ingestion of beef accounts for almost half of the total BDCF, followed by ingestion of milk.
- For C-14, the most significant pathways are ingestion of milk and drinking water from the well, followed by ingestion of other animal products, fish and crops.

Tab. 6-1: Biosphere dose conversion factors (BDCFs) for all radionuclides in the reference biosphere and alternative biosphere cases

Radionuclide	Reference biosphere dose conversation factor, Sv Bq^{-1}	Time to reach 90% of equilibrium BDCF, a
Ac-227	5.0E-16	7.1E+01
Ag-108m	1.3E-14	4.0E+02
Al-26	5.6E-12	4.0E+05
Am-241	1.6E-15	1.4E+03
Am-242m	7.4E-16	1.1E+04
Am-243	3.0E-14	2.8E+04
C-14	3.6E-16	1.0E+03
Ca-41	2.0E-15	5.6E+02
Cf-249	4.7E-15	1.6E+04
Cf-251	6.2E-15	2.8E+03
Cl-36	1.7E-14	1.0E+01
Cm-242	8.7E-19	4.0E+04
Cm-243	9.3E-17	2.8E+02
Cm-244	4.4E-17	8.9E+01
Cm-245	5.4E-14	2.2E+04
Cm-246	1.7E-14	1.8E+04
Cm-247	4.1E-13	1.6E+05
Cm-248	9.0E-13	1.3E+05
Co-60	6.9E-18	2.0E+01
Cs-135	2.2E-14	5.0E+04
Cs-137	1.9E-16	1.1E+02
Fe-60	1.4E-13	1.0E+01
Hg-194	6.3E-14	1.6E+03
Ho-166m	4.8E-15	5.0E+03
I-129	6.3E-13	2.8E+02
Mo-93	6.7E-15	3.2E+02
Nb-91	4.6E-18	2.8E+03
Nb-93m	6.5E-20	5.6E+01
Nb-94	2.1E-13	4.5E+04
Ni-59	2.1E-16	2.2E+04
Ni-63	8.2E-18	3.2E+02
Np-237	8.6E-14	1.1E+03

Radionuclide	Reference biosphere dose conversation factor, Sv Bq^{-1}	Time to reach 90% of equilibrium BDCF, a
Pa-231	6.8E-13	5.6E+04
Pb-202	1.3E-13	1.1E+05
Pb-205	6.6E-16	2.0E+05
Pb-210	6.1E-15	7.1E+01
Pd-107	7.4E-17	2.8E+03
Po-209	1.2E-14	3.2E+02
Po-210	9.9E-17	1.3E+00
Pu-238	1.5E-16	4.5E+04
Pu-239	7.4E-15	1.0E+05
Pu-240	1.1E-15	3.2E+04
Pu-241	5.4E-17	1.4E+03
Pu-242	7.4E-14	3.5E+05
Pu-244	1.1E-12	4.5E+05
Ra-226	4.8E-13	5.0E+03
Ra-228	4.5E-16	2.0E+01
Se-79	2.2E-14	1.1E+02
Si-32	1.9E-16	5.0E+02
Sm-151	2.0E-19	3.2E+02
Sn-121m	3.4E-17	1.4E+02
Sn-126	1.2E-13	5.6E+03
Sr-90	9.1E-15	7.9E+01
Tc-99	2.2E-15	6.3E+01
Th-228	1.6E-17	6.3E+00
Th-229	2.8E-13	2.0E+04
Th-230	6.3E-12	7.1E+04
Th-232	4.2E-12	8.9E+04
Ti-44	9.4E-14	8.9E+00
U-232	5.8E-14	2.2E+02
U-233	4.0E-13	1.6E+04
U-234	4.0E-13	4.5E+04
U-235	3.0E-13	1.6E+04
U-236	2.2E-13	8.9E+03
U-238	2.5E-13	1.0E+04
Zr-93	1.1E-15	8.9E+04

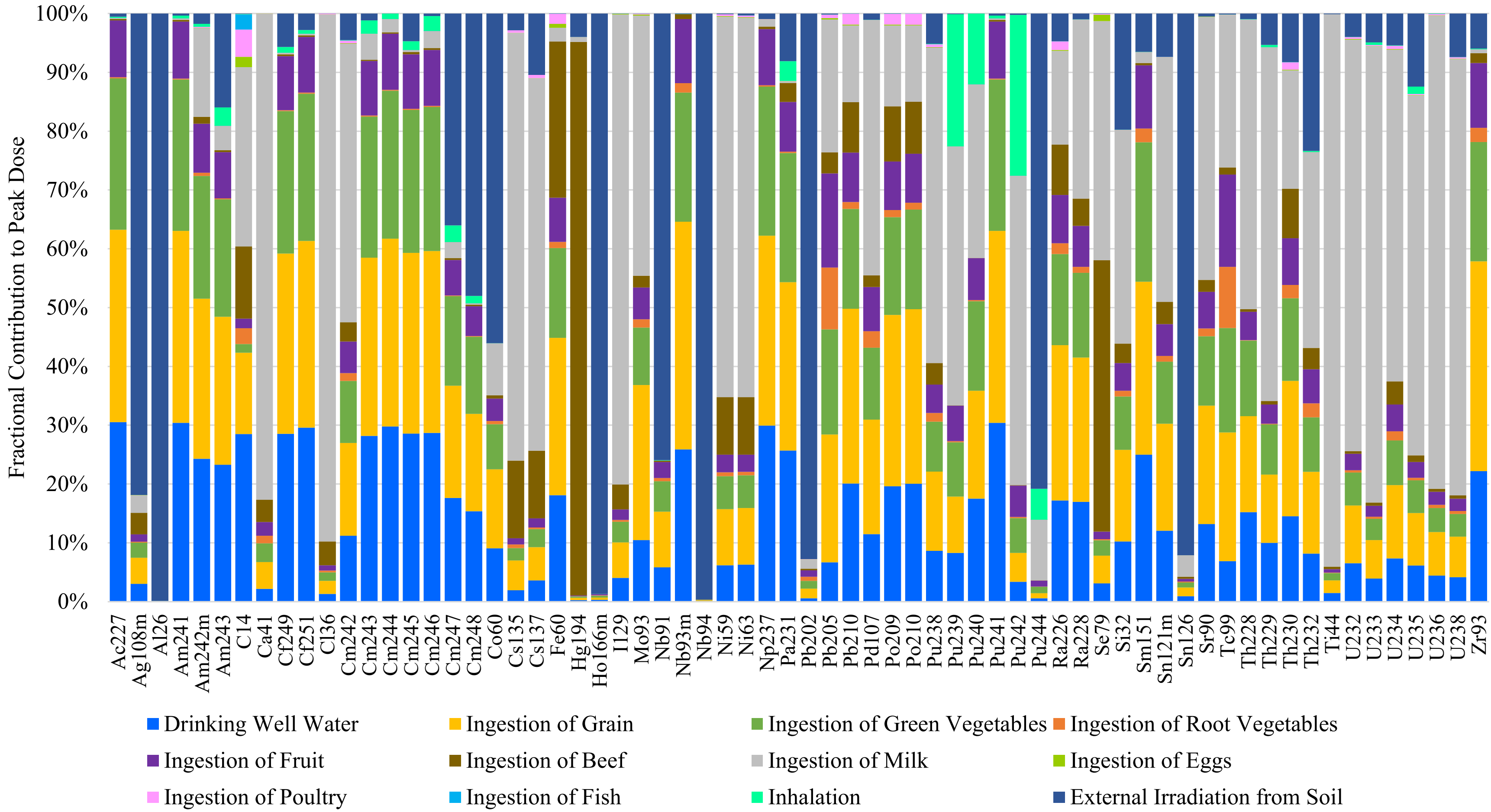

Fig. 6-1: Contributions to BDCFs by exposure pathway for each radionuclide, for the reference biosphere case

BDCFs for the warmer-drier climate, cold climate and drained farmland cases are presented in Tab. 6-2, including comparison to the reference biosphere case.

The highest BDCFs result from the warmer-drier climate case, which are on average a factor of three higher than the reference BDCFs, whereas, for a small number of radionuclides, the increase can be up to about a factor of ten. This is due to lower water flows through the shallow aquifer in the warmer-drier climate case, and hence the lower degree of dilution, as well as the increased use of well water for irrigation. Relatively mobile radionuclides (i.e. those with a low degree of retention, including Cl-36 and Ca-41) are most affected by these changes. Mass transfer processes, notably erosion, are more important for radionuclides that are more effectively retained on solids, and there is less distinction between the reference and warmer-drier climate cases with regard to this (e.g. the soil erosion rate is the same).

BDCFs for the drained farmland case were, for most radionuclides, reduced to 10%-75% of the reference BDCFs. This results from an absence of irrigation with groundwater (there surface water is transferred to the topsoil, reflecting flooding in the drained farmland case, but no water is used from the local aquifer for irrigation) as well as different assumptions on human habits compared to the reference biosphere case, including less food being grown locally. The only radionuclide that has a higher BDCF in the drained farmland case compared to the reference biosphere case is Pu-240 (around 20% higher); this is caused by the increased sorption of radionuclides on topsoil (the K_d value is doubled for all radionuclides, reflecting higher organic content of the drained farmland soil), the degree of retention of Pu-240 and its progeny, and the very long-lived nature of its progeny (see Section 5.5.1).

Despite the notably conservative assumptions in the cold climate case (e.g. that the exposure group obtains 50% of its meat and all milk from the biosphere area, despite the low productivity), BDCFs are between one and four orders of magnitude lower than the reference BDCFs for most radionuclides. Changes in comparison to the reference biosphere case are highly radionuclide-dependent, with BDCFs for some radionuclides (e.g. Cl-36) decreasing by more than five orders of magnitude, whereas other radionuclides only decrease by a factor of two (e.g. Nb-94). More significant reductions occur for radionuclides for which ingestion of crops and animal produce are important. These reductions result from lower irrigation of crops, no irrigation of pasture and lower local fractions for food produce. Lower reductions occur for radionuclides that are well retained on solids, have long half-lives and have relatively high external dose coefficients. The gradual erosion release to the topsoil is important for these radionuclides in the reference biosphere case and still occurs in the cold climate case, hence the difference in BDCFs for these radionuclides is more limited. However, it is also notable that these radionuclides generally tend to take a long time to reach equilibrium. In practice, cold conditions may not persist long enough for equilibrium to be achieved. Conditions may have progressed to full glacial conditions, or have warmed towards reference conditions. Even so, the BDCFs provide a measure of the effect of differing biosphere conditions and provide confidence that potential impacts under cold climate conditions would be noticeably lower than the reference biosphere conditions.

Tab. 6-2: Biosphere dose conversion factors (BDCFs) for all radionuclides in the biosphere cases, compared to the reference biosphere case. Ratios greater than 1 indicate that the BDCF is higher in the alternative biosphere case than in the reference biosphere case

Radionuclide	Biosphere dose conversation factor, Sv Bq^{-1}			Ratio to reference BDCF (alternative:reference)		
	Warmer-drier	Drained farmland	Cold climate	Warmer-drier	Drained farmland	Cold climate
Ac-227	8.5E-16	1.2E-16	3.5E-20	1.7	0.24	6.9E-05
Ag-108m	8.7E-14	5.1E-15	1.7E-18	6.7	0.40	1.3E-04
Al-26	5.9E-12	2.4E-12	3.6E-12	1.1	0.43	6.3E-01
Am-241	2.9E-15	4.1E-16	7.2E-19	1.8	0.25	4.4E-04
Am-242m	2.1E-15	2.6E-16	2.6E-17	2.9	0.35	3.5E-02
Am-243	5.8E-14	1.3E-14	3.6E-15	2.0	0.44	1.2E-01
C-14	9.2E-16	2.2E-16	1.0E-17	2.6	0.62	2.8E-02
Ca-41	2.2E-14	2.8E-16	1.3E-18	10.7	0.14	6.4E-04
Cf-249	8.6E-15	1.4E-15	7.9E-17	1.8	0.29	1.7E-02
Cf-251	1.1E-14	1.6E-15	2.2E-17	1.7	0.27	3.6E-03
Cl-36	1.6E-13	7.5E-16	7.0E-20	10.0	0.05	4.2E-06
Cm-242	4.8E-18	4.9E-19	8.9E-20	5.6	0.56	1.0E-01
Cm-243	1.5E-16	2.8E-17	5.3E-18	1.7	0.31	5.7E-02
Cm-244	7.5E-17	1.4E-17	1.3E-18	1.7	0.31	3.0E-02
Cm-245	1.0E-13	1.7E-14	1.8E-15	1.9	0.32	3.3E-02
Cm-246	3.0E-14	5.1E-15	4.8E-16	1.8	0.29	2.8E-02
Cm-247	1.5E-12	2.2E-13	1.7E-13	3.8	0.53	4.3E-01
Cm-248	3.3E-12	5.1E-13	4.5E-13	3.7	0.57	5.0E-01
Co-60	1.6E-17	6.8E-19	1.6E-22	2.3	0.10	2.2E-05
Cs-135	1.2E-13	1.6E-14	7.7E-15	5.4	0.73	3.6E-01
Cs-137	3.7E-16	6.5E-18	5.5E-21	2.0	0.03	2.9E-05
Fe-60	1.2E-12	3.4E-14	7.6E-18	8.4	0.24	5.4E-05
Hg-194	1.3E-13	6.1E-15	3.1E-16	2.0	0.10	4.9E-03
Ho-166m	1.1E-14	3.5E-15	3.5E-16	2.3	0.74	7.3E-02
I-129	5.6E-12	4.2E-14	4.4E-17	8.9	0.07	6.9E-05
Mo-93	6.2E-14	1.5E-15	5.1E-19	9.2	0.23	7.6E-05
Nb-91	9.5E-18	2.0E-18	7.9E-20	2.0	0.44	1.7E-02
Nb-93m	1.1E-19	1.4E-20	3.4E-24	1.7	0.21	5.2E-05
Nb-94	6.3E-13	2.1E-13	1.0E-13	3.0	1.00	5.0E-01
Ni-59	1.3E-15	2.6E-17	3.5E-18	6.0	0.12	1.7E-02

Radionuclide	Biosphere dose conversation factor, Sv Bq^{-1}			Ratio to reference BDCF (alternative:reference)		
	Warmer-drier	Drained farmland	Cold climate	Warmer-drier	Drained farmland	Cold climate
Ni-63	1.7E-17	5.1E-19	3.2E-22	2.0	0.06	3.9E-05
Np-237	6.7E-13	3.5E-14	6.9E-16	7.8	0.41	8.1E-03
Pa-231	1.6E-12	2.6E-13	9.2E-14	2.3	0.39	1.4E-01
Pb-202	2.9E-13	1.3E-13	1.1E-13	2.2	0.99	8.3E-01
Pb-205	1.7E-15	4.1E-16	1.6E-16	2.5	0.62	2.4E-01
Pb-210	1.1E-14	9.7E-16	1.2E-19	1.8	0.16	2.0E-05
Pd-107	6.1E-16	1.9E-17	2.1E-19	8.3	0.26	2.9E-03
Po-209	2.2E-14	1.9E-15	6.0E-19	1.8	0.16	5.0E-05
Po-210	1.8E-16	1.6E-17	1.7E-21	1.8	0.16	1.7E-05
Pu-238	9.2E-16	9.1E-17	1.7E-17	6.1	0.61	1.2E-01
Pu-239	9.7E-15	6.5E-15	4.4E-15	1.3	0.89	5.9E-01
Pu-240	1.9E-15	1.4E-15	4.8E-16	1.7	1.22	4.3E-01
Pu-241	9.6E-17	1.4E-17	2.4E-20	1.8	0.25	4.5E-04
Pu-242	8.4E-14	3.9E-14	3.1E-14	1.1	0.52	4.2E-01
Pu-244	1.2E-12	5.1E-13	6.4E-13	1.1	0.45	5.6E-01
Ra-226	9.4E-13	1.1E-13	2.3E-15	2.0	0.23	4.7E-03
Ra-228	8.2E-16	6.1E-17	1.5E-20	1.8	0.14	3.2E-05
Se-79	1.9E-13	1.1E-15	1.4E-18	8.8	0.05	6.5E-05
Si-32	3.9E-16	2.3E-17	3.5E-20	2.1	0.13	1.9E-04
Sm-151	3.6E-19	4.4E-20	2.6E-23	1.8	0.22	1.3E-04
Sn-121m	6.6E-17	3.6E-18	2.7E-21	1.9	0.11	7.9E-05
Sn-126	1.3E-12	7.4E-14	9.1E-15	10.9	0.61	7.4E-02
Sr-90	1.9E-14	1.1E-15	2.7E-19	2.1	0.13	2.9E-05
Tc-99	3.3E-14	6.5E-16	1.9E-19	15.4	0.30	8.6E-05
Th-228	2.9E-17	1.9E-18	3.6E-22	1.8	0.12	2.3E-05
Th-229	6.3E-13	1.4E-13	1.8E-14	2.2	0.49	6.3E-02
Th-230	1.9E-11	2.7E-12	9.4E-13	3.0	0.43	1.5E-01
Th-232	1.6E-11	2.8E-12	1.5E-12	3.8	0.67	3.5E-01
Ti-44	6.8E-13	1.8E-15	4.5E-19	7.2	0.02	4.8E-06
U-232	1.2E-13	3.6E-15	9.8E-19	2.0	0.06	1.7E-05
U-233	2.4E-12	3.4E-13	2.6E-14	6.0	0.84	6.5E-02
U-234	2.5E-12	2.5E-13	4.7E-14	6.3	0.62	1.2E-01
U-235	1.6E-12	1.9E-13	1.9E-14	5.5	0.64	6.3E-02

Radionuclide	Biosphere dose conversation factor, Sv Bq^{-1}			Ratio to reference BDCF (alternative:reference)		
	Warmer-drier	Drained farmland	Cold climate	Warmer-drier	Drained farmland	Cold climate
U-236	1.1E-12	1.3E-13	4.2E-15	5.1	0.58	1.9E-02
U-238	1.4E-12	1.6E-13	8.7E-15	5.4	0.62	3.4E-02
Zr-93	3.2E-15	4.1E-16	9.9E-17	3.0	0.39	9.4E-02

6.3 Sensitivity analyses

Additional calculations have been undertaken to explore sensitivity of the biosphere modelling to assumptions, including biosphere characteristics, and to identify important processes and parameters. A set of deterministic sensitivity cases is presented and discussed in Section 6.3.1 and probabilistic sensitivity calculations are presented in Section 6.3.2.

6.3.1 Deterministic sensitivity cases

Four deterministic sensitivity cases are considered that explore the impact of different lifestyles, sites (subdivided into larger and smaller biospheres) or discharge assessments to the reference biosphere case:

- S1: Exploration of assumptions on self-sufficient lifestyles;
- S2: Characteristics of local systems (bounded by two cases: "smaller" site and "larger" site);
- S3: Discharge directly to surface water.

These are described in more detail in the following sections.

Specification of sensitivity case S1: exploration of assumptions on self-sufficient lifestyles

The assumption of a self-sufficient lifestyle and maximum use of local resources, typically deriving 100% of food for the local population from the 2.275 km^2 of the reference biosphere case, is pessimistic. In practice, with present-day lifestyles, much of human food is not grown locally and/or the local contribution to food is small because agricultural products are gathered and effectively homogenised over areas that would be significantly larger. This case explores the degree of pessimism introduced by this assumption by calculating BDCFs for the reference biosphere case based on more typical lifestyle assumptions.

Alternative, and still somewhat pessimistic, assumptions are provided in Tab. 6-3, based on the general assumptions that:

- even for a community with emphasis on use of locally produced food, a 20% contribution for most pathways would be more reasonable; and
- members of the community would spend, on average, 2/3 of their average lifespan in the local area.

Tab. 6-3: Parameters used in the S1 sensitivity case based on more realistic lifestyle assumptions compared to the reference biosphere case

Exposure pathway	Local fraction		Discussion
	Reference	Sensitivity	
Beef	100%	20%	See discussion above
Milk and dairy produce	100%	50%	Taking into consideration a greater potential for milk to be regularly supplied locally compared to meat
Chicken meat and eggs	100%	50%	Greater potential for chickens to be raised locally
Grain	100%	20%	Based on the example of obtaining bread from a local farmer. This is still relatively pessimistic because grain would typically be grown/gathered over a wider area
Fruit and vegetables	100%	20%	See discussion above
Fish	10%	10%	Retain the reference assumption
Drinking water from local aquifer	100%	100%	Retain the reference assumption
Animal water from local aquifer	100%	100%	Retain the reference assumption
Animal feed from local area	100%	100%	Retain the reference assumption
External irradiation	100%	66%	See discussion above
Inhalation	100%	66%	Same as for external irradiation

Specification of sensitivity case S2, varying site characteristics

This case explores the sensitivity of BDCFs to characteristics of the local biosphere system, including notably different areas and hydrology. The cases chosen reflect cases BG-8 and BG-10 from Nagra (2014). BG-8 is representative of a relatively small valley with little water flow in the local aquifer and river, and BG-10 is representative of a relatively large valley with higher flow in the local aquifer and river. These cases were shown to bound the BDCFs from a wide range of site-specific cases considered in Nagra (2014) and are based on more detailed characterisation in Haldimann & Schatzmann (2014).

Tab. 6-4 gives the parameter values used in each sensitivity case compared to the reference biosphere case. Where parameters are not listed, values are unchanged from the reference biosphere case. The smaller biosphere case (based on BG-8 in Nagra (2014)) has an area of only 0.1 km^2, whereas the application of BDCFs assumes that all of the radionuclides in groundwater from depth discharge to the modelled biosphere area. This is a notably pessimistic assumption for the small biosphere case (e.g. the repository footprint would have a width scale around 1000 m).

Tab. 6-4: Parameters used in the S2 sensitivity case, varying site characteristics compared to the reference biosphere case

The smaller and larger biospheres are consistent with cases BG-8 and BG-10 in (Nagra 2014). Note that the BG-10 valley section is wider and shorter than the reference biosphere case, with an overall larger size.

Parameter	**Value**		
	Reference	**Smaller biosphere**	**Larger biosphere**
Biosphere area, A_f (km^{-2})	2.275	0.1	3.0
Flux of contaminated groundwater from depth to the near-surface local aquifer, F_{CL} (m^3/a)	1.3E+5	1.0E+4	1.0E+6
Flux of uncontaminated groundwater to the local aquifer, F_{UL} (m^3/a)	1.48E+6	9.0E+4	9.0E+6
Length of surface water body, l_W (m)	3.5E+3	1.1E+3	1.3E+3
Depth of surface water body, d_W (m)	3.25	0.10	4.25
Width of surface water body, w_W (m)	100	1	131
Thickness of local aquifer, l_L (m)	20	7	17

Specification of sensitivity case S3, with discharge directly to surface water

This sensitivity case explores the potential consequence of radionuclides releases in groundwater direct to a river in comparison to release to a local aquifer. In this case, drinking water for humans and animals and water for irrigation are also drawn from the river.

This case is consistent with case BG-1 in Nagra (2014).

Results of the deterministic sensitivity cases

Fig. 6-2 shows the results of the deterministic sensitivity cases for all radionuclides by giving the ratio between the calculated BDCFs in the sensitivity cases compared to the reference biosphere case.

In the case exploring the degree of pessimism in self-sufficient reference lifestyle assumptions (S1), the calculated BDCFs are lower than the reference BDCFs by a factor of between 1.5 and 5 for each radionuclide. This results directly from the lower fraction of foodstuffs consumed from the contaminated area and the lower occupancy fraction. Radionuclides (including Se-79) strongly linked to the consumption of beef or grain most significantly impact the BDCFs because the local fraction for these foods is reduced by a factor of five (see Tab. 6-3). The case is indicative of the safety margin introduced by assuming self-sufficiency within the local biosphere area.

Sensitivity case S2 explores the potential effect of the characteristics of the local biosphere area by bounding the calculation with smaller and larger areas. The smaller biosphere is only 0.1 km^2, but it is effectively assumed to receive the full release and support a self-sufficient community of approximately 10 individuals[14]. The effect on BDCFs for the smaller biosphere (BG-8) differs for

[14] Based on a population density of about 100 people per km^2 (see Section 3.2.1).

each radionuclide and, depending on the importance of different exposure pathways, increases by a factor of 15-65 compared to the reference biosphere case. The difference for each radionuclide is shown in Fig. 6-2. By contrast, BDCFs for the larger biosphere (BG-10) are a factor of 1.1-5.5 smaller than the reference biosphere case. The spread in the BDCFs between the smaller and larger biosphere cases is about a factor of 80 for most radionuclides and is indicative of the sensitivity to biosphere area and hydrology/hydrogeology. The degree of sensitivity to the characteristics of the local biosphere area is consistent with what was observed in Nagra (2014).

Sensitivity case S3 explores the effect of radionuclide release directly into surface water rather than into the local aquifer, with water for irrigation and drinking drawn from the river rather than groundwater. For most radionuclides, the resulting BDCF is two to five orders of magnitude below that of the reference biosphere case due to the increased dilution and avoidance of retention/ingrowth within the local aquifer. For three radionuclides (Th-228, Po-210, Cm-242), the calculated BDCF in this case is a factor of two to three higher than in the reference biosphere case. These radionuclides are notable by having the shortest half-lives of those studied (see Tab. 5-23), so they are retained long enough within the local aquifer to decay prior to reaching the topsoil/surface in the reference calculations. Direct release to surface water in this sensitivity case means that there is less opportunity for radioactive decay prior to potential exposures. In this case, the potential dose due to ingestion of fish is significantly higher for all radionuclides and becomes the most significant pathway for C-14. In addition to demonstrating the generally lower dose consequences that would arise with groundwater discharge to a river, the case is indicative of potential exposure rates that could occur downstream, especially given an increasing flow rate.

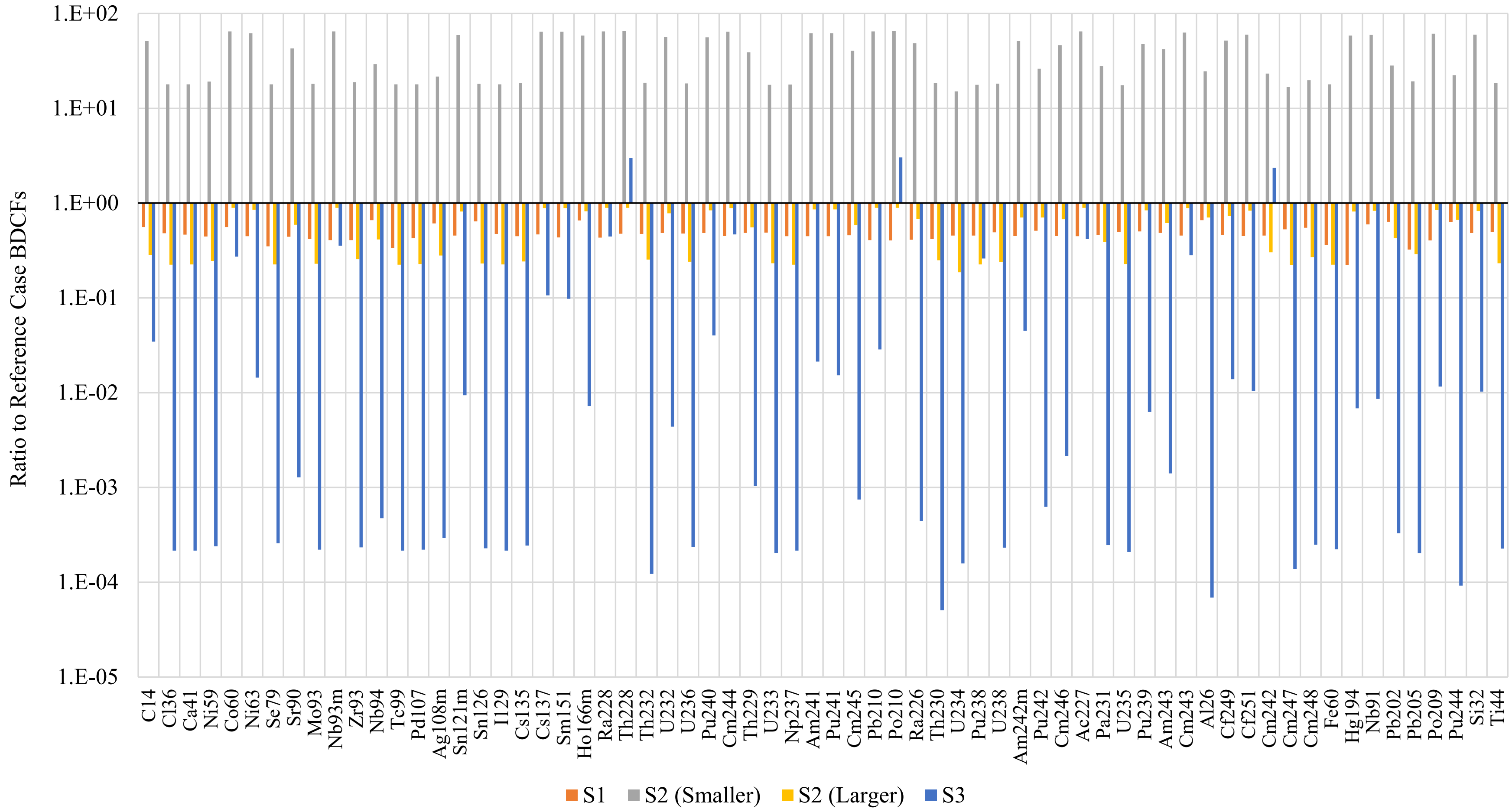

Fig. 6-2: Ratio of BDCFs to the reference results for each of the sensitivity cases: more realistic lifestyle assumptions (S1); alternative characteristics of the local system (S2); and discharge directly to surface water (S3)

A value greater than 1 means the sensitivity case BDCF is higher than the reference BDCF.

6.3.2 Probabilistic sensitivity analysis

Probabilistic sensitivity calculations have been undertaken to explore sensitivity to parameters not previously explored via the alternative biospheres and the deterministic sensitivity cases.

The objective of the probabilistic analyses is to identify important processes and parameters. The calculations do not aim to provide precise uncertainty bounds on BDCFs. For this reason, uniform or log-uniform distributions are specified for the varied parameters rather than more refined parameter distributions[15]. Nonetheless, the sampled parameters vary over plausible ranges.

Specification of probabilistic sensitivity analysis

The biosphere model parameters are listed in Tab. 6-5 and Tab. 6-6; these tables identify whether the parameters vary in the sensitivity analyses and, if so, in the associated ranges used.

To assess the sensitivity of the reference biosphere model to these parameters, a single probabilistic calculation was undertaken varying all the sampled parameters over the specified ranges with 10,000 samples. The strength of correlation between each of the varied parameters and the BDCFs provides an indication of the relative sensitivity to the associated uncertainty.

[15] A log-uniform distribution is preferred where ranges span more than about one order of magnitude, otherwise, a uniform distribution is used.

Tab. 6-5: Identification of parameters varied in the probabilistic sensitivity analyses; this table includes all parameters required for modelling radionuclide transport in the compartment model

The table identifies whether the parameters are sampled and, for those that are sampled, an associated range is specified; brief notes are also provided. OM is an acronym for "order of magnitude".

Parameter	**Sample?**	**Range**	**Notes**
Biosphere area, A_f	No	-	Explored in sensitivity case S2
Diffusion coefficient in water, D_0	No	-	Taken to be a fixed value
Evapotranspiration, d_{ETF}	No	-	Explored in alternative climate cases
Rainfall, d_{ETP}	No	-	Explored in alternative climate cases
Runoff, d_{RO}	No	-	Uncertainty in range of near-surface hydrogeology explored in alternative biosphere cases and deterministic sensitivity cases
Capillary rise, d_{Capil}	No	-	Uncertainty in range of near-surface hydrogeology explored in alternative biosphere cases and deterministic sensitivity cases
Irrigation rate of groundwater from the local aquifer, $Irri_L$	No	-	Explored in alternative climate cases
Irrigation rate of surface water, $Irri_W$	No	-	Explored in sensitivity case S3
Specified water flows (water inputs), F_i	No	-	Uncertainty in range of near-surface hydrogeology explored in alternative biosphere cases and deterministic sensitivity cases
Release to local aquifer, Rel_L	No	-	Effectively a binary option that is used in the reference biosphere case
Release to surface water, Rel_W	No	-	Explored in sensitivity case S3
Erosion rate, m_e	No	-	Explored in cold climate case
River sediment deposition rate to land, m_{SL}	No	-	Included in the drained farmland case

Parameter	Sample?	Range	Notes
Deposition rate of uncontaminated sediment to land, m_{dep}	Yes	Uniform 0 – 0.2 k m^{-2} a^{-1}	Varying over a plausible range; reference value is zero.
Turnover rate of river bed sediment, κ_S	Yes	Uniform 0.5 – 1.5 a^{-1}	Varying over a plausible range around the reference value of 1 a^{-1}
Soil mass transferred from the deep soil to the topsoil per unit biomass of deep burrowing fauna (e.g. worms), w_D	Yes	Uniform 10 – 30 a^{-1}	Varying over a plausible range around the reference value of 20 a^{-1}
Biomass of deep burrowing fauna (travelling between the deep soil and the topsoil), m_D	Yes	Uniform 0.05 – 0.15 kg m^{-2} a^{-1}	Varying over a plausible range around the reference value of 0.1 kg m^{-2} a^{-1}
Concentration of suspended solids in water / porewater, α_i	Yes	Surface water: log uniform 0.02 – 0.2 kg m^{-3} Log uniform 0.0002 – 0.005 kg m^{-3}	Varying over a plausible range around the reference values of 0.1 kg m^{-3} for surface water and 0.001 kg m^{-3} for other materials Separate scaling factor for each type of material
Total porosity, ε_i	Yes	Vary by uniform 0.1 on either side of reference value	Separate scaling factor for each type of material Surface water value is calculated, so is not varied here
Thickness of compartment/length of surface water, l_i	No	-	Explored in sensitivity case S2
Solid (grain) density of compartment material, ρ_i	Yes	Uniform 2450 – 2850 kg m^{-3}	Density of water remains fixed at 1000 kg m^{-3} Separate scaling factor for each type of material
Volumetric moisture content, θ_i	Yes	For unsaturated compartments, vary saturation over uniform 0.65-0.85	Changed to saturation from specified volumetric water content for sensitivity analysis to ensure correlation with total porosity Not sampled for saturated compartments Separate scaling factor for each type of material
Tortuosity of solid compartment material, T_i	Yes	Calculate from equation C.11 in Klos et al. (1996), varying μ in that equation over uniform 1.4-2.4	Calculated to be consistent with sampled porosity and some variation introduced

Parameter	Sample?	Range	Notes
Depth of surface water, d_W	No	-	Explored in sensitivity case S2
Width of surface water, w_W	No	-	Explored in sensitivity case S2
Gas loss from topsoil to elsewhere, λ_{TE}	No	-	Value based on detailed consideration and separate modelling for C-14
Sorption coefficients, K_d	Yes	Log uniform +/- 2 OM	Suitable for sensitivity analyses Separate scaling factors used for different classes of materials

Tab. 6-6: Identification of parameters varied in the probabilistic sensitivity analyses; this table includes all parameters required for assessing potential exposures based on the radionuclide transport modelling

The table identifies whether the parameters are sampled and, for those that are sampled, an associated range is specified; brief notes are also provided. OM is an acronym for "order of magnitude".

Parameter	Sample?	Range	Notes
Background dust concentration, a_r	Yes	Log uniform 5E-9 – 5E-7 kg m^{-3}	Varied over plausible range around reference value of 5E-8 kg m^{-3}
High dust concentration, a_h	Yes	Log uniform 2E-6 – 5E-5 kg m^{-3}	Varied over plausible range around a central value of 1E-5 kg m^{-3}, reference biosphere case assumes zero occupancy at this level
Total annual energy intake from food, E_0	No	-	Taken to be fixed value, degree of pessimism in assuming completely self-sufficient diet explored through S1

Parameter	Sample?	Range	Notes
Fraction of the animal's water demand obtained from the well, f_A	No	-	Alternative assumptions explored in sensitivity case S3
Fraction of the total food energy from each foodstuff, f_f	No	-	Explored in sensitivity case S1 and in cold climate case
Local fractions for each exposure pathway	No	-	Alternative assumptions explored in sensitivity case S1
Fraction of suspended solid material removed by filtering before consumption, f_{filter}	Yes	Uniform 0 – 0.5	Pessimistically set at 0 for reference biosphere case
Fraction of drinking water obtained from the local aquifer, f_{well}	No	-	Alternative assumptions explored in sensitivity case S3
Effective dose coefficient due to external irradiation, G	No	-	Uncertainty in effective dose coefficients is not explored in the sensitivity analyses, e.g. deterministic values are prescribed in regulations
Effective dose per unit intake via ingestion, H_{ing}	No	-	Uncertainty in effective dose coefficients is not explored in the sensitivity analyses, e.g. deterministic values are prescribed in regulations
Effective dose per unit intake via inhalation of particulates and gases, H_{inh}	No	-	Uncertainty in effective dose coefficients is not explored in the sensitivity analyses, e.g. deterministic values are prescribed in regulations
Annual volume of air inhaled by the exposed individual, I_{air}	No	-	Exposure group assumptions explored through deterministic case relating to lifestyle assumptions
The exposed individual's total annual fluid consumption via drinking water and milk, I_{fluid}	No	-	Exposure group assumptions explored through deterministic case relating to lifestyle assumptions
Daily water consumption by the animal, I_{wc}	Yes	Cattle: uniform 0.02 – 0.04 $m^3\ d^{-1}$ Chickens: 0.0001 – 0.0003 $m^3\ d^{-1}$	Varied around reference values of 0.03 $m^3\ d^{-1}$ for cattle and 0.0002 $m^3\ d^{-1}$ for chickens

Parameter	Sample?	Range	Notes
Daily feed consumption by animals, I_{pc}	Yes	Cattle: uniform 15 – 25 kg d^{-1} Chickens: uniform 0.05 – 0.09 kg d^{-1}	Varied around reference values of 20 kg d^{-1} for cattle and 0.07 kg d^{-1} for chickens
Fraction of the intercepted contamination absorbed to the internal parts of the plant, f_{abs}	Yes	Uniform factor of 5 around reference value	This means absorption remains zero where appropriate Separate scaling factors for each crop
Fraction of internal contamination associated with the edible part of the plant, f_{trans}	Yes	Uniform 0.5 – 1	Reference pessimistically adopts a value of 1 Separate values for each crop
Fraction of contamination in the internal edible part of the plant that remains after food processing, f_{int}	Yes	Uniform 0.5 – 1	Reference pessimistically adopts a value of 1 Separate values for each crop
Fraction of the external intercepted contamination associated with the edible part of the plant after food processing, f_{ext}	Yes	Pasture: fixed 1 Root veg.: fixed 0 Grain: uniform 0.1 – 0.4 Green veg.: uniform 0.25 – 0.75 Fruit: uniform 0.05 – 0.25	Plausible ranges adopted around reference values of 0.25 for grain, 0.5 for green vegetables and 0.15 for fruit
Fraction of the external soil contamination retained on the edible part of the plant after food processing, f_{Soil}	No	-	Varied via S_{crop}
Time between the start of irrigation and harvest (or grazing/cutting for pasture), t_1	Yes	Uniform 0.2 – 0.3 a	Plausible range around reference value of 0.25 a Separate values for each crop
Time between the end of irrigation and harvest (or grazing/cutting for pasture), t_2	Yes	Pasture: uniform 0.01 – 0.03 Grain: uniform 0.05 – 0.1 Green veg.: uniform 0.01 – 0.03 Root veg.: uniform 0.02 – 0.06 Fruit: uniform 0.01 – 0.03	Plausible ranges around reference values of 0.02 for pasture, green vegetables and fruit, 0.075 for grain, and 0.04 for root vegetables

Parameter	**Sample?**	**Range**	**Notes**
Interception factor for the crop, μ_{crop}	Yes	Uniform 2 – 4 $m^2\ kg^{-1}$	Plausible range around reference value of 3 $m^2\ kg^{-1}$ Same range for all crops
Dry weight above-ground plant biomass at the time of irrigation, B_{crop}	Yes	Pasture: uniform 0.5 – 0.9 kg m^{-2} Grain: uniform 1.25 – 1.75 kg m^{-2} Green veg.: uniform 1 – 1.4 kg m^{-2} Root veg.: uniform 0.8 – 1.2 kg m^{-2} Fruit: uniform 0.6 – 1 kg m^{-2}	Plausible ranges around reference values of 0.7 kg m^{-2} for pasture, 1.5 kg m^{-2} for grain, 1.2 kg m^{-2} for green vegetables, 1 kg m^{-2} for root vegetables and 0.8 kg m^{-2} for fruit
Fresh-weight edible yield at the time of harvest, Y_{crop}	Yes	Pasture: uniform 1 – 1.4 kg m^{-2} Grain: uniform 0.51 – 0.71 kg m^{-2} Green veg.: uniform 2 – 4 kg m^{-2} Root veg.: uniform 3 – 5 kg m^{-2} Fruit: uniform 1.5 – 3.5 kg m^{-2}	Plausible ranges around reference values of 1.2 kg m^{-2} for pasture, 0.61 kg m^{-2} for grain, 3 kg m^{-2} for green vegetables, 4 kg m^{-2} for root vegetables and 2.5 kg m^{-2} for fruit Given that this is sensitivity analysis, correlation with standing biomass at time of irrigation is ignored
Transfer factor between dry-weight soil and fresh-weight edible crop, K_{crop}	Yes	Log uniform +/- 2 OM C-14: uniform +/- factor of 2	Plausible ranges adopted. For C-14, the range is constrained and based on difference between recommendations arising from work supporting Guillemot et al. (2024). Use separate scaling factors for the different crops
Transfer factor from animal ingestion to eggs, K_{eggs}	Yes	Log uniform +/- 2 OM	Plausible ranges adopted
Concentration ratio relating the concentration in edible fish to the concentration in surface water on a fresh-weight basis, K_{ff}	Yes	Log uniform +/- 2 OM	Plausible ranges adopted
Transfer factor from animal ingestion to meat, K_{meat}	Yes	Log uniform +/- 2 OM	Plausible ranges adopted Use separate scaling factors for beef and chicken

Parameter	Sample?	Range	Notes
Transfer factor from animal ingestion to milk, K_{milk}	Yes	Log uniform +/- 2 OM	Plausible ranges adopted
Thickness of the atmosphere affected by degassing and associated with inhalation, l_A	Yes	Uniform 1.5 – 2.5 m	Varied over plausible range around reference value of 2 m
Fractional annual occupancy at the occupational/elevated dust concentration, O_f	Yes	Uniform 0 – 0.01	Varied over a plausible range; the reference biosphere case assumes no occupancy at a high dust load
Soil contamination on the edible crop, based on wet soil and fresh-weight crop, S_{crop}	Yes	Pasture: uniform 0.05 – 0.15 kg kg^{-1} Grain: uniform 5E-5 – 1.3E-4 kg kg^{-1} Green veg.: uniform 1E-4 – 3E-4 kg kg^{-1} Root veg.: uniform 0 – 1E-4 kg kg^{-1} Fruit: uniform 1E-4 – 4E-4 kg kg^{-1}	Varied over plausible ranges around reference values; default value for root vegetables is zero, but range applied for sensitivity calculations gives potential for some root vegetables to be consumed washed but unpeeled
Mean annual wind velocity, v_A	Yes	Uniform 2.1E+7 – 6.1E+7 m a^{-1}	Varied over plausible range around reference value of 4.1E+7 m a^{-1}
Weathering loss term from the external surfaces of the crop, W_{crop}	Yes	Uniform 7 – 27 a^{-1} C-14: fixed high rate	Varied over plausible range around reference value of 17 a^{-1}; exception is for C-14, for which photosynthetic uptake dominates and is treated separately
Average weight of an egg, w_{egg}	No	-	Confident there is sufficient accuracy in reference value
Density of milk, w_{milk}	No	-	Confident there is sufficient accuracy in reference value
Ratio by weight of fresh pasture to hay, Z	Yes	Uniform 2.5 – 7.5	Varied over plausible range around reference value of 5
Energy content of the foodstuff, η_f	No	-	Contributes to ingestion rates by people, which are explored through sensitivity case S1
Volatile element degassing rate, λ_{dg}	No	-	Based on supporting calculation for C-14

Results of the probabilistic sensitivity analysis

The strength of correlation between sampled parameters and BDCFs helps to indicate the most important parameters (among those sampled, given the specified ranges) and reveals important associated processes and pathways. Tab. 6-7 lists the parameters most strongly correlated with BDCF for each of the radionuclides. The table highlights sorption and transfer factors as they are among the most important parameters varied in the probabilistic calculation. Uncertainty concerning sorption and transfer factors for trace elements in environmental systems can span several orders of magnitude. In the sensitivity analysis, these ranges dominate over uncertainty for other parameters listed in Tab. 6-5 and Tab. 6-6, which vary over much smaller ranges.

Importance of sorption

Tab. 6-7 highlights that the degree of retention of radionuclides within the local aquifer is an important process for many of the radionuclides. The negative correlation demonstrates that the higher the degree of retention (i.e. the higher the K_d), the lower the resulting BDCF. Greater retention within the local aquifer reduces concentrations in groundwater (reducing potential exposures from drinking water or from irrigation) and allows for radionuclides to decay before reaching the surface (particularly those that are shorter-lived).

Sorption on biosphere materials is clearly important in determining the behaviour of radionuclides. It is a characteristic that varies between locations, reflecting the substrate and local geochemistry. Nagra's biosphere sorption database has been subject to review in support of the RBG assessment (Metcalfe et al. 2023). The review specifically considers substrates and geochemical conditions anticipated in the reference and alternative biosphere systems for Northern Switzerland.

Importance of transfer factors to foods

Beyond correlation between sorption, which can be site-specific, and the associated availability of radionuclides for root uptake, transfer factors to crops and animal produce are less site-specific (e.g. Sheppard (2005)). Transfer factors used in Nagra's biosphere modelling draw on international compilations.

Radionuclides that exhibit a relatively low degree of retention (i.e. with low K_d) are more mobile with groundwater and surface water. For these radionuclides (including Cl-36 and I-129), sorption is less important, and Tab. 6-7 shows that transfer factors to milk become important.

The international database of transfer factors from feed to cows' milk has been subject to a relatively recent update in Howard et al. (2017). The updated database for transfer to cows' milk has been used in support of Nagra's biosphere modelling for the RBG (see Section 5.4.7), and provides the basis for many of the associated parameter values, including those for Cl-36 and I-129.

Indicative ranges for the BDCFs

Although the main aim of the probabilistic sensitivity analyses has been to help identify important processes and parameters, the sampled parameters have been varied over plausible ranges, so the results are indicative of uncertainty associated with the BDCFs relating to those parameters that have been varied. Fig. 6-3 shows the 5th and 95th percentiles for the BDCFs resulting from the probabilistic sensitivity analyses for each radionuclide, along with the reference BDCF.

Fig. 6-3 indicates ranges in BDCFs spanning two to three orders of magnitude. These reflect the notable range in uncertainty bounds for important parameters including sorption, which can vary over several orders of magnitude (Metcalfe et al. 2023), and transfer factors to crops and animal produce (IAEA 2010, Howard et al. 2017, Sheppard 2005).

Tab. 6-7: Rank correlation coefficients between sampled parameters and reference BDCFs

Only the three most strongly correlated parameters with absolute rank correlations ≥ 0.1 are shown for each radionuclide.

Radio-nuclide	**Parameters with highest absolute rank correlation coefficients with BDCF (correlation coefficients given in brackets)**
Ac-227	Aquifer K_d (-0.99)
Ag-108m	Topsoil K_d (0.62), aquifer K_d (-0.55), transfer factor to beef (0.2)
Al-26	Deep Soil K_d (0.56), aquifer K_d (0.56), sedimentation (-0.32)
Am-241	Aquifer K_d (-0.97)
Am-242m	Aquifer K_d (-0.58), transfer factor to milk (0.36), deep soil K_d (0.23)
Am-243	Aquifer K_d (-0.92), transfer factor to milk (0.16), deep soil K_d (0.13)
C-14	Transfer factor to milk (0.58), transfer factor to beef (0.35), aquifer K_d (-0.32)
Ca-41	Transfer factor to milk (0.68), topsoil K_d (0.48), transfer factor to pasture (0.23)
Cf-249	Aquifer K_d (-0.98)
Cf-251	Aquifer K_d (-0.99)
Cl-36	Transfer factor to milk (0.86), transfer factor to beef (0.21), transfer factor to pasture (0.18)
Cm-242	Transfer factor to milk (0.58), deep soil K_d (0.35), transfer factor to beef (0.15)
Cm-243	Aquifer K_d (-0.95), transfer factor to milk (0.12)
Cm-244	Aquifer K_d (-0.96), transfer factor to milk (0.12)
Cm-245	Aquifer K_d (-0.94), weathering rate for grain (-0.13)
Cm-246	Aquifer K_d (-0.93), transfer factor to milk (0.16), weathering rate for grain (-0.1)
Cm-247	Aquifer K_d (0.78), deep soil K_d (0.36), transfer factor to milk (0.19)
Cm-248	Deep soil K_d (0.73), topsoil K_d (0.25), weathering rate for grain (-0.21)
Co-60	Aquifer K_d (-0.96), transfer factor to milk (0.18), topsoil K_d (0.1)
Cs-135	Transfer factor to milk (0.66), transfer factor to pasture (0.3), transfer factor to beef (0.3)
Cs-137	Aquifer K_d (-0.86), transfer factor to milk (0.39), transfer factor to beef (0.17)
Fe-60	Transfer factor to beef (0.76), transfer factor to milk (0.2), weathering rate for grain (-0.18)
Hg-194	Aquifer K_d (-0.72), transfer factor to beef (0.64)
Ho-166m	Aquifer K_d (-0.94), topsoil K_d (0.27), deep soil K_d (0.1)
I-129	Transfer factor to milk (0.85), transfer factor to beef (0.22), topsoil K_d (0.16)
Mo-93	Transfer factor to milk (0.59), topsoil K_d (0.51), transfer factor to grain (0.24)
Nb-91	Aquifer K_d (-0.98), topsoil K_d (0.12)
Nb-93m	Aquifer K_d (-0.99)
Nb-94	Aquifer K_d (-0.65), deep soil K_d (0.58), topsoil K_d (0.31)
Ni-59	Transfer factor to milk (0.7), transfer factor to beef (0.27), aquifer K_d (-0.26)

Radio-nuclide	Parameters with highest absolute rank correlation coefficients with BDCF (correlation coefficients given in brackets)
Ni-63	Aquifer K_d (-0.85), transfer factor to milk (0.4), transfer factor to beef (0.15)
Np-237	Transfer factor to milk (0.42), weathering rate for grain (-0.36), aquifer K_d (0.31)
Pa-231	Aquifer K_d (-0.85), transfer factor to beef (0.22), deep soil K_d (0.17)
Pb-202	Deep Soil K_d (0.66), aquifer K_d (-0.36), sedimentation (-0.24)
Pb-205	Aquifer K_d (0.46), transfer factor to milk (0.39), deep soil K_d (0.25)
Pb-210	Aquifer K_d (-0.95), transfer factor to milk (0.17), transfer factor to beef (0.13)
Pd-107	Transfer factor to milk (0.66), topsoil K_d (0.39), deep soil K_d (0.22)
Po-209	Aquifer K_d (-0.94), transfer factor to milk (0.19), transfer factor to beef (0.16)
Po-210	Aquifer K_d (-0.95), transfer factor to milk (0.17), transfer factor to beef (0.13)
Pu-238	Transfer factor to milk (0.63), deep soil K_d (0.38), transfer factor to beef (0.16)
Pu-239	Aquifer K_d (-0.69), transfer factor to milk (0.43), deep soil K_d (0.24)
Pu-240	Aquifer K_d (-0.79), transfer factor to milk (0.4), deep soil K_d (0.13)
Pu-241	Aquifer K_d (-0.97)
Pu-242	Transfer factor to milk (0.70), aquifer K_d (-0.29), deep soil K_d (0.22)
Pu-244	Transfer factor to milk (0.64), aquifer K_d (0.51), deep soil K_d (0.13)
Ra-226	Aquifer K_d (-0.90), transfer factor to milk (0.24), transfer factor to beef (0.17)
Ra-228	Aquifer K_d (-0.93), transfer factor to milk (0.28)
Se-79	Transfer factor to beef (0.59), transfer factor to milk (0.56), weathering rate for pasture (-0.16)
Si-32	Aquifer K_d (-0.90), transfer factor to milk (0.34)
Sm-151	Aquifer K_d (-0.98)
Sn-121m	Aquifer K_d (-0.89), transfer factor to milk (0.37)
Sn-126	Topsoil K_d (0.63), deep soil K_d (0.48), transfer factor to milk (0.33)
Sr-90	Aquifer K_d (-0.79), transfer factor to milk (0.46), topsoil K_d (0.13)
Tc-99	Topsoil K_d (0.77), transfer factor to milk (0.34), transfer factor to pasture (0.16)
Th-228	Aquifer K_d (-0.89), transfer factor to milk (0.39)
Th-229	Aquifer K_d (-0.73), transfer factor to milk (0.59)
Th-230	Transfer factor to milk (0.51), deep soil K_d (0.31), transfer factor to beef (0.29)
Th-232	Transfer factor to milk (0.63), aquifer K_d (0.34), deep soil K_d (0.27)
Ti-44	Transfer factor to milk (0.96), weathering rate for pasture (-0.14), weight ratio of hay to fresh pasture (0.13)
U-232	Aquifer K_d (-0.81), transfer factor to milk (0.52)
U-233	Transfer factor to milk (0.86), deep soil K_d (0.33), weight ratio of hay to fresh pasture (0.11)
U-234	Transfer factor to milk (0.64), deep soil K_d (0.39), aquifer K_d (0.33)
U-235	Transfer factor to milk (0.81), deep soil K_d (0.34), aquifer K_d (0.13)

Radio-nuclide	**Parameters with highest absolute rank correlation coefficients with BDCF (correlation coefficients given in brackets)**
U-236	Transfer factor to milk (0.89), deep soil K_d (0.2), transfer factor to pasture (0.12)
U-238	Transfer factor to milk (0.79), deep soil K_d (0.26), aquifer K_d (0.23)
Zr-93	Deep soil K_d (0.36), transfer factor to grain (0.3), transfer factor to beef (0.27)

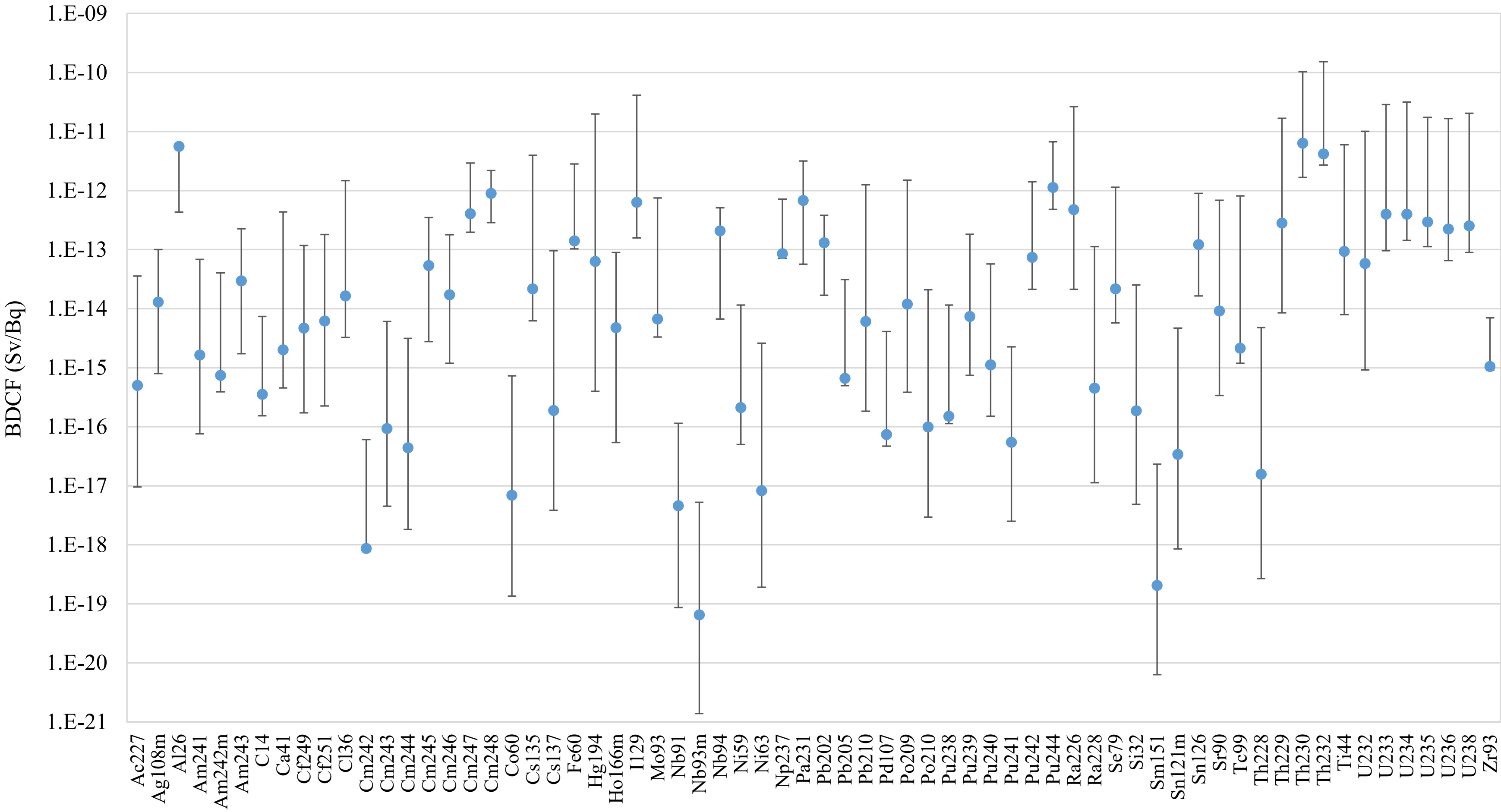

Fig. 6-3: Reference BDCFs (blue markers) and 5[th] and 95[th] percentiles (black lines) for each radionuclide from the probabilistic sensitivity calculation

The biosphere parameters varied are listed in Tab. 6-5 and Tab. 6-6; not all parameters were varied, because some are explored in the deterministic sensitivity cases and/or in the range of biosphere cases considered.

7 Summary and conclusions

This report fully describes Nagra's biosphere modelling in support of the general licence application (RBG), undertaken within the framework of the post-closure safety assessment, which supports the post-closure safety case and the site-selection for geological disposal.

Biosphere modelling was conducted using a systematic and transparent approach, in line with ENSI regulations (ENSI 2018, ENSI 2023, ENSI 2020) and international guidelines reflected in the enhanced BIOMASS methodology (Lindborg et al. 2022). The context is explained, and a reference biosphere system is identified based on present-day conditions in Northern Switzerland. Alternative cases exploring different assumptions regarding climate (warmer-drier and cold climate conditions) and morphology (shallower groundwater) are also identified. The biosphere systems to be modelled are then described. On the basis of those descriptions, conceptual models of radionuclide release, transport and potential exposure are developed. Those models are then formulated mathematically and supported by associated data. The models are implemented in the SwiBAC code to deliver BDCFs in support of Nagra's RBG post-closure safety case.

Nagra's biosphere modelling approach was established thirty years ago and has been continuously refined through iterative assessments. Nagra's experience in developing and justifying the biosphere modelling approach has contributed to the development of international guidelines through BIOMOVS II (1996), IAEA (2003) and the international collaborative BIOPROTA forum[16].

The objective of the biosphere modelling is to provide a measure of the performance of Nagra's repository system, as well as a quantitative measure of radiological safety, through dose calculations. The disposed waste inventory will remain hazardous for a long time after closure, and some radionuclides can potentially reach the biosphere over extremely long timescales. The timescales involved and the dynamic nature of the biosphere mean that there is significant uncertainty about the nature of the surface environment into which radionuclide releases might occur in the distant future. Given these uncertainties, biosphere modelling aims to deliver an overall pessimistic assessment to help ensure that potential dose consequences to humans who inhabit the affected region are not underestimated. The pessimistic evaluation of potential doses to humans is taken to provide an overall measure of environmental safety.

Today's biosphere in Northern Switzerland is used as an analogue for conditions that could arise in the future. The assessment focuses on releases to environments that support a wide range of potential exposure pathways; in this context, this means biosphere modelling focuses on radionuclide releases in groundwater to river valleys that support agricultural use. Radionuclide releases in groundwater to lakes are also possible, but the additional dilution that would typically occur in lakes in Northern Switzerland mean that potential dose consequences would be lower than releases to river valleys, so the assessment of radionuclide releases to lakes is not explicitly necessary.

The earth's climate will change over the timescales relevant to the assessment, with cycles of interglacial and glacial conditions. Reference calculations are undertaken on the basis of today's climate given that it is recognisably well characterised and understood, and supports productive agricultural use. Periods of warmer and colder climates are possible; these are explored through the alternative cases for warmer-drier and cold climates. Warmer-wetter conditions are also possible but are not explicitly assessed because they have previously been shown to result in lower dose consequences as higher rainfall causes additional dilution.

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[16] www.bioprota.org (retrieved 29.02.2024)

To avoid an overly pessimistic assessment, biosphere modelling aims to be realistic in terms of representing radionuclide migration in the biosphere, but pessimistic in evaluating potential dose consequences. This pessimism is achieved by assuming that the biosphere in the area of potential radionuclide releases is occupied by a population making maximum reasonable use of local resources through a self-sufficient lifestyle. This ensures that a wide range of potential exposure pathways are included in the dose assessment.

Biosphere modelling is conducted based on a constant unit release of radionuclides in groundwater into a local aquifer. The modelling delivers biosphere dose conversion factors (BDCFs) that are achieved when equilibrium is reached between the unit releases and potential doses. The BDCFs demonstrate that different potential exposure pathways are important for different radionuclides, reflecting properties such as radionuclide mobility and radiotoxicity. Drinking groundwater from the local aquifer, consuming milk from the local area and eating local crops are shown to be important factors regarding many radionuclides. Additionally, in the case of some radionuclides, external irradiation and ingestion of local beef are also shown to be important.

BDCFs for a warmer-drier climate are higher than those for a present-day climate due to lower groundwater and river flow rates under warmer-drier conditions, which reduces the degree of mixing. It also reflects increased irrigation requirements under warmer-drier climate conditions as irrigation relying on local groundwater presents an important pathway for some radionuclides to reach crops and the topsoil. On average, the BDCFs increase by a factor of three whereas, for a small number of radionuclides, the increase can be up to about a factor of ten.

BDCFs for radionuclide releases to a valley where the land has been drained for farming are up to about 6.5 times lower than those for the reference biosphere case. This reflects reduced irrigation requirement for wetter soils and the more limited range of agriculture that would be feasible under such conditions.

BDCFs for the cold climate case are typically between one and four orders of magnitude lower than those based on the present-day climate. In most cases, the reduction is very significant, reflecting the absence of groundwater irrigation and a lower potential for the use of local resources. The reduction in BDCFs is less dramatic for radionuclides that are strongly sorbed in the local aquifer and tend to reach the topsoil by weathering and erosion.

Sensitivity calculations exploring more realistic assumptions regarding local resource usage demonstrate a reduction in BDCFs by up to a factor of about five and illustrate the safety margin inherent in making assumptions of self-sufficiency. It is notable that even with the local population obtaining just 20% of their food and 50% of their milk, chicken and eggs from the local area, the sensitivity case remained relatively pessimistic.

Sensitivity calculations exploring BDCFs for radionuclide releases to valleys that differ in characteristics compared to the reference biosphere case included release to a very small valley (0.1 km^2) with lower groundwater flows and a larger valley (3 km^2) with higher groundwater flows compared to the reference biosphere case (2.275 km^2). The smaller valley/lower flow case resulted in BDCFs that are about 15 – 65 times higher than the reference biosphere case, and the larger valley/higher flow case resulted in BDCFs that are up to about a factor of five lower. These two cases illustrate the importance of the local characteristics, especially valley size and near-surface hydrology. They serve to demonstrate the potentially realistic spread of results, although it should be noted that the assumption that 100% of the discharge occurs to a single section of a valley is particularly pessimistic in the case of the small biosphere. The site context in Northern Switzerland also means that deeper groundwater may be expected to discharge to larger valleys.

A sensitivity calculation exploring direct release of deeper groundwater to surface water resulted in BDCFs that are typically between two to five orders of magnitude lower than those for the reference biosphere case. This reflects the higher flow rate in the river compared to the groundwater flow rate through the local shallow aquifer.

Probabilistic sensitivity calculations help to identify further processes and parameters important in determining the BDCFs. These highlight the importance of sorption on the local aquifer. In this context, it should be noted that the biosphere modelling for the RBG has been supported by a review and update to Nagra's biosphere sorption database (Metcalfe et al. 2023). The calculations also demonstrate the importance of parameters determining radionuclide transfer to crops and animal produce (especially to milk). These parameters draw on the most recent international compilations of biosphere data.

The alternative biosphere cases and the range of sensitivity cases illustrate the degree of uncertainty associated with the BDCFs. However, these uncertainties should be interpreted in the context of key pessimistic assumptions, which are summarised in Tab. 7-1.

As in SGT-E2, Nagra's biosphere modelling for the RBG has been implemented in the SwiBAC code. The code was developed within an accredited quality assurance framework that complies with software development standards. The BDCF calculations have also been verified through the independent adaptation of models in the general-purpose AMBER compartment modelling code. The latter has been used for the sensitivity calculations, including the probabilistic analyses.

Tab. 7-1: Key assumptions in biosphere modelling for the RBG

Assumption	Discussion
The local population is considered to be self-sufficient to the greatest degree practicable, and spend 100% of their time within the local area.	This maximises the range of potential exposure pathways and the extent of potential exposure. Today, humans draw a notable proportion of their food and drinking water from outside their local environment and spend time elsewhere, so the assumption of self-sufficiency is pessimistic.
The reference biosphere case assumes that a shallow groundwater well is present close to the point of radionuclide releases and intercepts an associated plume.	If groundwater wells are not present, or do not intercept the plume, then potential exposures arising from drinking water for humans as well as for irrigation and drinking water for livestock would be significantly reduced.
Equilibrium BDCFs are used in the assessment.	This assumes that radionuclide releases in groundwater occur long enough for equilibrium between releases and potential doses to be achieved. It can take several tens of thousands of years for calculated doses to approach equilibrium (see Tab. 6-1), so that equilibrium may not be achieved for some radionuclides and the use of BDCFs is pessimistic.
Use of BDCFs assumes that 100% of radionuclides in groundwater from depth discharge to a single stretch of valley.	In practice, radionuclides in groundwater from depth would become dispersed and may discharge to different locations.
Periods when humans would not be present due to glaciations are not explicitly evaluated.	Application of BDCFs to radionuclide releases effectively assume that humans may always be present when peak releases occur.
Biosphere modelling focuses on releases to environments that tend to result in higher potential exposures.	Potential for radionuclide releases to alternative biosphere conditions that would result in lower potential exposure rates are not evaluated, including release to typical lakes in Northern Switzerland and/or releases under warmer-humid climate conditions.
Pasture consumed by livestock is assumed to be irrigated with local groundwater.	Although irrigation of pasture is feasible (e.g. to harvest hay), it is not common. Irrigation is a key pathway for radionuclides in groundwater to contaminate fodder.

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