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Environmental Change in Post-closure Safety Assessment of Solid Radioactive Waste Repositories

Report of Working Group 3 Reference Models for Waste Disposal of EMRAS II Topical Heading Reference Approaches for Human Dose Assessment

Environmental Modelling for Radiation Safety (EMRAS II) Programme

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ENVIRONMENTAL CHANGE IN POST-CLOSURE SAFETY ASSESSMENT OF SOLID RADIOACTIVE WASTE REPOSITORIES

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ENVIRONMENTAL CHANGE IN POST-CLOSURE SAFETY ASSESSMENT OF SOLID RADIOACTIVE WASTE REPOSITORIES

REPORT OF WORKING GROUP 3
REFERENCE MODELS FOR WASTE DISPOSAL
OF EMRAS II TOPICAL HEADING
REFERENCE APPROACHES FOR HUMAN DOSE ASSESSMENT

ENVIRONMENTAL MODELLING FOR
RADIATION SAFETY (EMRAS II) PROGRAMME

INTERNATIONAL ATOMIC ENERGY AGENCY
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FOREWORD

Environmental assessment models are used for evaluating the radiological impact of actual and potential releases of radionuclides to the environment. They are essential tools for use in the regulatory control of routine discharges to the environment and also in planning measures to be taken in the event of accidental releases. They are also used for predicting the impact of releases which may occur far into the future, for example, from underground radioactive waste repositories. It is important to verify, to the extent possible, the reliability of the predictions of such models by a comparison with measured values in the environment or with predictions of other models.

The IAEA has been organizing programmes of international model testing since the 1980s. These programmes have contributed to a general improvement in models, in the transfer of data and in the capabilities of modellers in Member States. IAEA publications on this subject over the past three decades demonstrate the comprehensive nature of the programmes and record the associated advances which have been made.

From 2009 to 2011, the IAEA organized a programme entitled Environmental Modelling for Radiation Safety (EMRAS II), which concentrated on the improvement of environmental transfer models and the development of reference approaches to estimate the radiological impacts on humans, as well as on flora and fauna, arising from radionuclides in the environment.

Different aspects were addressed by nine working groups covering three themes: reference approaches for human dose assessment, reference approaches for biota dose assessment and approaches for assessing emergency situations. This publication describes the work of the Reference Models for Waste Disposal Working Group.

The IAEA wishes to express its gratitude to all those who participated in the work of the EMRAS II programme and gratefully acknowledges the valuable contribution of T. Lindborg (Sweden), G. Smith (United Kingdom) and the organizations which hosted Working Group interim meetings, namely, the Helmholtz Zentrum München and Nagra (National Cooperative for the Disposal of Radioactive Waste). The IAEA officer responsible for this publication was G. Proehl of the Division of Radiation, Transport and Waste Safety.

CONTENTS

SUMMARY

The IAEA's BIOMASS programme provided extensive guidance on the development of reference biospheres and included examples of how to develop reference biospheres in different assessment contexts. Since the end of the BOMASS programme in 2001 significant international projects have addressed some of the critical issues identified during BIOMASS and the methodology has been used and adapted in many site generic and site specific assessments of post-closure safety of radioactive waste repositories, and significant model inter-comparison and radionuclide specific model development exercises have been carried out under the BIOPROTA[1] international collaboration programme.

Noting this wide variety of international and project specific work, WG3 of EMRAS II was set up with the objectives to:

- Review, describe and present different approaches for developing reference biosphere models appropriate for assessments of exposures to humans in performance assessment studies of repositories for disposal of solid radioactive waste.
- Include in that review, alternative approaches to address the effects of environmental change, such as changes in climate, land use, agricultural practices and human behaviour.
- Provide recommendations on the content and application of models that address the above issues over a wide range of environmental situations.

The scope of the work included assessment of post-emplacement environmental and human health impacts of solid radioactive waste in purpose built repositories for solid radioactive waste. WG3 activities and output presented here include:

- Use of data for present day conditions at a range of different sites with different climate and other characteristics which might be considered as suitable analogues for future conditions at a particular site in question;
- Modelling of the important features of the soil plant system in different climate and other conditions;
- Use of dynamic system modelling of climate and landscape change in order to better understand the possible future biosphere conditions at a site, on a site specific basis;
- A brief review of international recommendations and national requirements and guidance on how to address environmental change in demonstrating compliance with post-closure protection objectives.

It is noted that additional benefit was gained from exchange of experience and technical developments presented and discussed during WG3 meetings.

It is recommended that the above work is used as basis for developing a common generic framework for structuring the biosphere part of a post-closure assessment, taking into account environmental change.

[1] http://www.bioprota.org

1. BACKGROUND, OBJECTIVES AND SCOPE

1.1. BACKGROUND OF THE EMRAS II PROGRAMME

The IAEA orgranized a programme from 2009 to 2011 entitled Environmental Modelling for RAdiation Safety (EMRAS II), which concentrated on the improvement of environmental transfer models and the development of reference approaches to estimate the radiological impacts on humans, as well as on flora and fauna, arising from radionuclides in the environment.

The following topics were addressed in nine working groups:

Reference Approaches for Human Dose Assessment

- Working Group 1: Reference Methodologies for Controlling Discharges of Routine Releases
- Working Group 2: Reference Approaches to Modelling for Management and Remediation at NORM and Legacy Sites
- Working Group 3: Reference Models for Waste Disposal

Reference Approaches for Biota Dose Assessment

- Working Group 4: Biota Modelling
- Working Group 5: Wildlife Transfer Coefficient Handbook
- Working Group 6: Biota Dose Effects Modelling

Approaches for Assessing Emergency Situations

- Working Group 7: Tritium Accidents
- Working Group 8: Environmental Sensitivity
- Working Group 9: Urban Areas

The activities and the results achieved by the Working Groups are described in individual IAEA Technical Documents (IAEA-TECDOCs). This report describes the work of the Reference Models for Waste Disposal Working Group.

1.2. BACKGROUND FOR EMRAS II WORKING GROUP 3: REFERENCE MODELS FOR WASTE DISPOSAL

The IAEA's BIOMASS programme provided extensive guidance on the development of reference biospheres and was completed in 2001 [1]. This included examples of how to develop reference biospheres in different assessment contexts. Since 2001, significant international projects have addressed some of the critical issues identified during the BIOMASS programme [1], notably the European projects:

- BIOCLIM [2] which considered how to address climate change, and
- BIOMOSA [3] which considered the application of the BIOMASS methodology at specific sites, as compared to a generic methodology application.

Significant model inter-comparison exercises have been carried out under the BIOPROTA international collaboration, which provides a forum for exchange of information and peer review among operators, regulators, technical support organizations and academics of the science behind the biosphere modelling assumptions. Recent projects set up within BIOPROTA have focused, among other things, on investigation of improved models for dose long term dose assessment for specific radionuclides, such as C-14 [4], Cl-36 [5, 6], Se-79 [7] and the U-238 series [8]. Another important development has been the update of IAEA's advice on data for important radionuclide dependent data [9].

Finally it is worth noting that the methodology described in IAEA-BIOMASS-6 [1] has been taken into account in many major repository assessment projects, some of which have been site generic, e.g. ONDRAF/NIRAS [10], NWMO [11] and NDA-RWMD [12], and some of which are site specific, e.g. ANDRA [13], KBS-3H [14] and US DOE [15], NWMO [16], Posiva [17] and SR-SITE [18]. These applications and variant approaches adopted in a wide variety of assessment contexts, as well as the other international work referred to above, provide a substantial basis for review and updating of the usefulness of the IAEA-BIOMASS-6 methodology [1]. This is now timely given that more than 10 years have passed since that methodology was developed.

According to the German 2008 Draft Safety Requirements Governing the Final Disposal of Heat-Generating Radioactive Waste[2], long-term radiological prognoses shall be performed on the basis of reference biosphere models. Accordingly, the German Federal Office for Radiation Protection (BfS), organized a workshop in August 2008, to obtain an overview of the experience gained with the Reference Biospheres Methodology and to identify priorities for future research and development. Participants included experts from various European countries (including Belgium, France, Germany, Sweden and the United Kingdom), representing a wide range of approaches to biosphere modelling within long-term safety assessments for geologic nuclear waste repositories. Key issues identified at the workshop [19] which warrant further consideration include:

- Environmental change, which can be climate driven but also includes related factors such as changes in landscape, and groundwater and sea levels, as well as changed land use by humans.
- Processes at the transition zone between the geosphere and the biosphere. A variety of potentially relevant geosphere-biosphere interfaces was identified, though it is recognized that the details will be site specific.
- Important migration and accumulation processes within the biosphere itself, which in many cases are radionuclide and/or site specific.

Noting all the above background material and the progress with repository site selection and site specific investigation, it was agreed that the EMRAS II Working Group (WG3) be set up with the objective to:

- Review, describe and present different approaches for developing reference biosphere models appropriate for assessments of exposures to humans in performance assessment studies of repositories for disposal of solid radioactive waste.

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[2] Final version from 2010, available at:
http://www.bmu.de/fileadmin/bmu-import/files/english/pdf/application/pdf/sicherheitsanforderungen_endlagerung_en_bf.pdf

— Include in that review, alternative approaches to address the effects of environmental change, such as changes in climate, land use, agricultural practices and human behaviour.
— Provide recommendations on the content and application of models that address the above issues over a wide range of environmental situations.

The scope of the work includes assessment of post-emplacement environmental and human health impacts of solid radioactive waste in purpose built repositories for solid radioactive waste.

Section 2 of this report describes the approach taken to addressing the issues raised above, and the set of Sub-Groups (SGs) formed to carry out the work. Section 3 summarizes and discusses the results of the SG activities in relation to the issues. Section 4 provides conclusions and recommendations. These sections are then followed by a series of appendices which set out the detailed work of the SGs which were prepared by participants in those SGs.

2. APPROACH TO CARRYING OUT THE STUDY

2.1. STAGES IN ANALYSIS

Following initial discussion of what is demonstrated to be a very complex set of issues [1], the following four step process was adopted to address the objectives of WG3.

2.1.1. Process orientated consideration of critical factors that may have a major influence on dose to man (Step 1)

Here the idea was to identify the processes using radio-ecological and assessment experience to identify important processes, based on existing work in BIOMASS, BIOCLIM, BIOPROTA, BIOMOSA and the national assessment projects which have been on-going, notably concerning:

- Climatic factors and climate change processes;
- Geosphere-biosphere interface processes;
- Geomorphological processes;
- Land use processes;

and then:

- To consider whether these factors are of more universal nature or are they specific to a particular site conditions or other aspects of the assessment context (as described in IAEA-BIOMASS-6 [1]);
- To consider whether models developed for one climate (e.g. temperate) are adequate to address the specific conditions of a changed climate.

It was also recognized that potentially significant processes during transitions, say, from one climate state to another, or during acute or extended stages of landform change, could significantly modify the distribution of radionuclides released to the biosphere. Furthermore, it was noted that these changes should logically be treated coherently with the rest of the repository assessment.

2.1.2. Learning from recent assessments and research (Step 2)

Consideration of how recent assessments and related research have addressed critical issues could be used to provide practical examples of how those issues have been addressed. Those assessments will have had specific assessment contexts attached to them, so it could be instructive to identify the assessment approaches used and to consider under what circumstances those issues need to be treated differently, and when common solutions can be effective.

2.1.3. Quantitative analysis of alternative approaches (Step 3)

It was anticipated that the work in steps 1 and 2 would throw up potentially important questions which could be examined though applying alternative modelling approaches. Scenarios related to these questions could be constructed and different methods for their analysis applied or developed. Consideration could be given to understanding of biosphere systems, development of conceptual models, development of mathematical representations of those systems and concepts, data requirements and uncertainty analysis.

2.1.4. Development of contributions to recommendations on biosphere assessment, models and data (Step 4)

The results from Steps 1–3 could then be used to provide answers to the following questions:

- Are the basic steps in the IAEA-BIOMASS-6 [1] methodology still relevant?
- What detailed improvements may be made to support future biosphere assessments for repositories, relevant to:
  - specific ecosystems and their site specific data,
  - specific climate systems and climate changes,
  - specific geosphere-biosphere interfaces, in constant conditions and under environmental changes/transitions,
  - the selection and justification of model discretization,
  - the assumptions for reference groups and food habits,
  - specific land use assumptions, and
  - specific regulatory requirements?

Given the different perspectives of WG participants, in terms of expertise, responsibilities and status of projects for radioactive waste repository development in different countries, it was clear that not all issues could be readily addressed by everyone. Four WG3 subgroups (SG) were therefore set up to address the issues and questions, taking into account different perspectives, as follows.

2.2. SUBGROUP OBJECTIVES AND SCOPE

2.2.1. SG1 Application of analogues

This SG was set up to explore the use of data for present day conditions at a range of different sites with different climate and other characteristics which might be considered as suitable analogues for future conditions at a particular site in question.

2.2.2. SG2 Soil-plant processes

This SG focused on the important features of the soil plant system. This was considered important because of the role of the foodchain in determining the most significant doses for the more significant radionuclides, such as Cl-36 and I-129, as determined from previous assessments. It is interesting to determine, for example, when accumulation, and hence the potential for root uptake, may give rise to larger doses via contamination of the foodchain than the direct contamination of foods arising from irrigation with contaminated well water. Soils may also become contaminated from below, depending upon the local near-surface hydrology in the area of release from the geosphere. Accumulation in soil is also very important for exposures due to external irradiation and inhalation of dust, e.g. generated in farming practices such as ploughing. Questions considered included:

- Which are the processes which will be affected by climate change in the soil plant system?
- Which are the transfer processes affecting discretisation?
- Which are the processes affecting water balance?
- How can we integrate these processes in overall repository performance assessment (PA) models?

The objective was to develop:

- Understanding relevant climate impact on the biosphere, and
- Understanding interactions between the vegetation, soils, land cover/land use and the climate system which affect radionuclide migration and accumulation in environmental media relevant to radiation exposure, notably soils and vegetation.

2.2.3. SG3 Application of dynamic analysis of future biosphere systems at specific sites

It was clear from the beginning that there are distinct modelling perspectives from those whose focus is environmental change and those who are primarily concerned with radiological impact assessment. It was therefore recognized that an important part of the project was to bring both of these perspectives together in providing recommendations and examples. Accordingly, noting the focus in SG1 and SG2 on static systems in different fixed climate states, SG3 explored the use of dynamic system modelling of climate and landscape change in order to better understand the possible future biosphere conditions at a site, on a site specific basis.

The main steps proposed for consideration were:

(1) Provide a system description (general characteristics).
(2) Identify processes and parameters potentially affected by environmental change.
(3) Show how these processes and parameters can be represented in a model.
(4) Assess how changes in relevant processes and parameters affect dose assessments.
(5) Identify processes and parameters of general importance in the context of environmental change.

2.2.4. SG4 Demonstrating compliance with protection objectives

This SG was intended to explore compliance demonstration and how that is affected by the need to take account of environmental change. Consideration was given to international recommendations, as provided by the IAEA and the International Commission on Radiological Protection (ICRP), and at the national level, in regulatory requirements and guidance. The objective was to identify how the protection objectives set out in the various in international documents, and related requirements and guidance on how to address environmental change, affects the content of repository assessment. The difference stages of reposity development were taken into account.

3. BIOSPHERE MODELLING AND ENVIRONMENTAL CHANGE: CONCLUSIONS FROM DIFFERENT PERSPECTIVES

3.1. APPLICATION OF ANALOGUES

In Appendix I, the set-up of a model to calculate Biosphere Dose Conversion Factors (BDCFs) for the exposure to different radionuclides of a self-sustaining population at the location of a high level radioactive waste deep geological repository is presented. The model's FEP list, interaction matrix and mathematical foundation of the model have been presented, following the BIOMASS methodology [1].

Furthermore, the model has been applied to different reference stations to examine the effects of different climates on BDCFs, taking into account how climatic factors influence radionuclide distribution in the biosphere and the relevant exposure pathways. On the time frame of interest in post-closure repository assessment, a change of climate to colder conditions might significantly affect the scope for agriculture, etc. On the other hand a climate change to warmer conditions relative to current conditions is possible; the climate may get drier or more humid. These changes influence the physical and chemical behaviour of radionuclides in the top soil layers and their transport through the food chain, as well as the agricultural and dietary habits of the exposed group.

Two scenarios are assumed for most of the analogue sites, defined by the geosphere-biosphere interface of groundwater. In the first scenario "rising groundwater", the groundwater table is high enough to provide all the water needed for agriculture directly. Soil humidity is regulated by a drainage system. In case of the contamination of the groundwater with radionuclides, a balance between the contamination in soil and water forms quickly. This scenario is mostly used for wetland and river floodplain soils. It is assumed that for the dry reference sites the groundwater level will be too low to use this scenario. In the second scenario "well" groundwater enters the biosphere as well water. It is assumed that water deficits of agriculture are balanced by irrigation with well water. The well water is also assumed to be used as drinking water for humans and animals. Contamination can also accumulate in standing groundwater discharge systems used for fish breeding. Four basic soil types sand, loam, clay and organic soils are included into the model to represent different possible locations and conditions for pasture or arable land. For these basic soil types, parameters for different radionuclides were derived from the literature.

The BDCF results are presented in substantial detail in Appendix I, for a relevant set of radionuclides, soil types, age groups and other factors. They demonstrate a pronounced influence of the amount of irrigation needed for agriculture on the peak doses. However, the resulting BDCFs have been demonstrated to be reasonably comparable with the results from other relevant assessments, illustrating the robustness of the model and the modelling approach. The most significant differences in results were related to BDCFs for Cl-36 and Se-79. This result lends support for the development of more detailed radionuclide specific models, as developed within BIOPROTA, see Section 1.

Appendix I clearly shows how other sites can be used as analogues for future different climate conditions at a particular site of interest. The approach does not directly address the effect of climate change on the biosphere landscape itself, nor the interface with the geosphere.

3.2. SOIL–PLANT PROCESSES

Appendix II records how SG2 investigated the impact of climate factors on a key part of the biosphere, the mechanisms relating to the incorporation of radionuclides in to crops from soil. Specifically, the source is irrigation with foliar adsorption and root uptake giving rise to accumulation in agricultural crops. Four groups contributed results addressing the central theme of the exercise (modelling the effects of climate change). Additional material was provided that allowed a discussion of accumulation processes due to the effects of local hydrology and corresponding redox conditions. The spatial and temporal discretisation of the model system was addressed and a comparison of model variability versus climate variability was made.

Participating models included simple and more complex compartment structures, static and variable water table height and two models which solve the full Richard's equation using time series for hydrologic input on a daily basis. The compartment models generally employed annual averaging of climate and other parameters.

Boreal, temperate and Mediterranean climate conditions were selected and data provided by participants for sites in their own national programmes which fitted the requirements of the exercise. Crop and soil conditions were assumed to be the same in each site so that the focus in the modelling would be on the treatment of climate factors. Calculations of soil concentration as a function of time and crop concentration by the two parallel mechanisms of foliar adsorption of contaminated irrigation water and root uptake from contaminated soil were selected as endpoints.

The results show that the even using the same basic site description the result differ according to the models used. There is an apparent difference in the participating models between the more generic and the more site specific model interpretations. This suggests that model uncertainties can be usefully explored in a dose assessment by using alternative models.

Furthermore, the uncertainty identified here, whether due to model or parameter uncertainty, should be propagated through to the dose calculations. The impact must be addressed either qualitatively or quantitatively through a validation of models and parameters.

Biosphere dose assessment models are abstracted from FEPs. A thorough review of all relevant FEPs is essential for developing assessment models for specific sites. This is emphasised here by the variation in interpretation of irrigation in the participating models. Further review of the treatment of irrigation in long-timescale assessment models would be beneficial.

Irrigation remains the most straightforward way of getting activity concentration into agricultural crops. For highly sorbed radionuclides with high sorption coefficients, k_d, the time taken to accumulate in soil is often longer than the timescale for chronic cultivation scenarios. However, results for geochemical zonation at the saturated/unsaturated zone boundary, seen in the results from the GEMA-10L model, also indicate the need for to review the FEPs associated with accumulation. For a release to the base of shallow soils, it is possible, depending on the radionuclide's k_d, to obtain concentrations in the rooting zone of soils that are close to those arising from direct irrigation scenarios.

Commonly, compartment models are used to describe ecosystems. Because a fundamental assumption behind compartmental models is instantaneous mixing of solute in each compartment, the spatial distribution of contaminants in the system is not always well represented. Therefore, the effect of model discretisation on modelling results should be analysed. There are indications that the use of temporal scales less than the traditional annual averaging might lead to differences in soil concentration. This use of interannual data should be pursued, particularly when used in conjunction with a dynamic plant sub-model and a variable water table height. One of the participating models employed a dynamic plant as part of the soil-plant system. Results were somewhat different and the reasons should be investigated, particularly as this model also employed a dynamic water table height.

3.3. APPLICATION OF DYNAMIC ANALYSIS OF FUTURE BIOSPHERE SYSTEMS AT SPECIFIC SITES

Appendix III illustrates how site specific dynamic consideration of environmental change can be implemented based on the Forsmark site in Sweden, but taking into account work done by SKB and Posiva. Illustrations taken from that work reflect the steps identified in Section 2.2.3 and additionally include a description of how the sub-system models in the overall PA can be made to fit together, consistent with the understanding of climate evolution scenarios, other effects such as land-rise, and the response of the landscape to that evolution.

The illustrative results show how the approach can be used to make a clear dynamic link between the points of radionuclide release from the geosphere to the temporally varying biosphere system above it. The results also quantitatively show how this can be important for the assessment of doses.

A set of parameters has been provided, potentially of generic relevance to the dynamic consideration of environmental change. It is clear that a more rapidly changing site is likely to need closer consideration of the dynamics of the system.

It can be understood that where sufficient site understanding has been established, it is possible to focus in detail on the key issues and, thereby avoid what might otherwise have been more conservative assumptions. Climate scenario and development of the biosphere (and the rest of the system) can be handled with realistic/plausible examples of lines of evolution as it is practically impossible to assign specific probabilities to the lines of evolution or to cover the full range of possible futures – the strategy to avoid endless speculation is to choose an illustrative set of scenarios, relevant to the assessment context.

3.4. DEMONSTRATING COMPLIANCE WITH PROTECTION OBJECTIVES

Review of international recommendations (Appendix IV) shows that environmental change is recognized as likely to occur over the timeframes of interest in post-closure repository safety. Furthermore this needs to be taken into account in safety assessments. However, the focus is upon addressing natural changes and this introduces uncertainty in relation to climate change, which is understood, at least in part, to be due to human influence.

Review of national requirements on past-disposal safety and related guidance on addressing environmental change shows that the level of prescription in national regulations and guidance varies. In some cases the assumptions to be made about environmental change and related biosphere changes, including human behaviour, are quite explicit. There are some variations in the timeframes for which quantitative assessment is required, but the use of more stylized approaches and complementary safety indicators for later times is a common trend. The more prescriptive examples naturally present scope for divergence from each other, and these in turn may reflect geographic and other locally specific factors. This reflects the comment in the MeSA report of NEA [20] that, ‘‘Greater differences exist between countries regarding the extent to which regulations allow simplified handling of the biosphere in the safety assessment', that is, compared with other aspects of the overall PA.

The reasons for the variation reflect that some assessment programmes are in early stages of development, i.e. concept demonstration or site generic, whereas other are closer to implementation, at the license application stage, while some facilities are already licensed. The effect of making an assessment different at different stages affects not only the amount of information available about a site, but also the nature of the more likely relevant releases from the geosphere and the nature of the arguments needed to give confidence in next steps. Clearly, approval for continued investigation does not require the same level of confidence as a license to operate a disposal facility. The level of prescription in requirements and guidance may follow the same stages, but also reflect the general regulatory framework in a country, as being more or less prescriptive.

This is a reflection that the assessment design is more or less defined by aspects of the assessment context [1]. However, that reference does not develop discussion very far on compliance demonstration in relation to environmental change.

The material in Appendix IV as well as the results of the other SG activities suggests the following main points in relation to compliance demonstration:

- It is recognized that environmental change is a material factor that will affect the radiological impact of radionuclide releases from the geosphere.
- The scope for such change needs therefore to be addressed in the biosphere part of the PA.
- Assumptions for human behaviour are difficult to predict with useful reliability, so current behaviour at sites today which have the characteristics expected in the future at the site of interest can be useful example {analogue} behaviours for use in the PA. However, if such are not currently exploited by humans (e.g. humans are absent) then it may also be useful to consider the exploitation potential for such sites, taking into account current technologies, or subsistence level societies. It is not considered useful to consider future developments in technology as these may be too many and varied.

4. CONCLUSIONS AND RECOMMENDATIONS

It is widely recognized that environmental change will affect the radiological impact arising from any eventual releases of radionuclides from radioactive waste repositories into the biosphere. This is reflected in international recommendations on post-closure safety. Clarification on the distinction between natural and anthropogenic environmental change could be useful. Consideration has been given here to a range of different approaches and techniques for addressing such change.

The first approach considered was the use of data for present day conditions at a range of different sites with different climate and other characteristics which might be considered as suitable analogues for future conditions at a particular site in question. With this approach, it is assumed that this set of analogous constant biosphere systems adequately captures the relevant range of future systems. Key issues have been identified as well as model development illustrated, much in line with the BIOMASS methodology. Within the constraints of the examples provided and reviewed, the dose assessment methods appear robust, with the main uncertainties being associated with a few key radionuclides.

The other main approach is to model explicitly the dynamic evolution of the biosphere in response to the main environmental change drivers, i.e. climate change and geomorphological changes, notably associated with sea-level change at coastal sites, but also potentially linked to erosion in areas of geological uplift. The approach demonstrated relies on integration of the modelling of the evolution of climate, hydrology, landform, radionuclide release from the geosphere, radionuclide migration and accumulation and land-use. The approach relies on detailed site specific characterisation of the biosphere system and how it is linked to the geosphere. It also yields relatively precise information on how radionuclides are most likely to enter the biosphere, potentially avoiding the use of overly conservative assumptions.

Detailed consideration has been given to the modelling of the soil-plant sub-system in a range of different fixed climate and other conditions. This information can be useful within the dynamic and analogue approaches, depending on the level of temporal discretisation adopted. It also provides a useful starting point for assessing transient effects linked to environmental change.

Both approaches have been demonstrated to be useful and can be considered complementary. The analogue approach may be especially useful at the early stages of repository development, as it is less data intensive and not so reliant on site specific information. The more explicitly dynamic approach may provide further safety assurance at later stages, and also provide a stronger demonstration of integrated understanding of the system under evaluation. The need to model change dynamically, and the level of work this implies, can be significantly dependent upon the rates of change and the susceptibility to change at the site in question. It may also depend on national requirements and guidance. Significant information has been provided in the Appendices to this report to support developments and further thinking in this context, with the identification of key issues, and features events and processes.

It may be noted that both main approaches rely on an understanding of likely scenarios for climate change, either to obtain the envelope of relevant analogues or to directly feed into the models for system evolution. It is some time since the BIOCLIM project addressed this issue and climate change modelling has been under considerable scrutiny and development since then. Noting this and the other factors mentioned above, the Working Group suggested that future work should provide a consensus approach to addressing climate change, by focusing on:

- Analyzing further the few key processes which drive environmental change (mainly climate change), and describing how a relevant future may develop on a global scale. These drivers are quantitative and can be extracted from existing scientific consensus on global historical climate evolution.
- Assuming that history will repeat itself in the long term, and using this analysis to describe the future or a small set of possible futures, which one might call 'reference futures'. These are not predictions but relevant examples to apply on specific questions in a safety assessment.
- Developing a conceptual framework that is valid on a global scale, and how that can be downscaled to provide information needed for site specific assessments.
- Applying the conceptual framework to a number of case studies, that would illustrate the methodology on specific sites, including the implications for dose assessment models. The latter should address both changes in the relevantly affected environment prior to any assumed radionuclide release to the biosphere as well as changes occurring after or while releases are assumed to occur, including possible transient effects which may have dose implications.

Such a consensus approach would be intended to provide a common generic framework for structuring the biosphere part of a post-closure assessment, taking into account environmental change.

APPENDIX I. USE OF ANALOGUES TO SUPORT LONG TERM SAFETY ASSESSMENT OF NUCLEAR WASTE REPOSITORIES WITH REFERENCE BIOSPHERES UNDER CHANGING CLIMATES

I.1. INTRODUCTION

To ensure safe storage for final disposal of high-level waste in stable geologic formations, long term safety assessments have to be carried out. For the eventuality of discharge of radionuclides out of the repository, the potential exposure of the population to ionizing radiation has to be assessed. An important approach for the assessment of potential radiation exposure is the modelling of radionuclide transport through the geosphere and the biosphere to humans. Because of the complexity of the modelled processes, the development of one single large model is not feasible. The modelling task is divided in sub models, considering separately the transport through geological formations, the food chain and other relevant pathways.

Exposure is estimated for a population obtaining all its food and drinking water from the potentially contaminated area around the repository. As an important condition this self-sustaining group is behaving as if no contamination were present. Therefore, possible prevention and security measures against the uptake of contaminants are not included in the model.

Several glacial periods occurred in central Europe during the last million years. Because of this, a change of climate to colder conditions has to be taken into account during the assessment time frame. On the other hand a climate change to warmer conditions relative to current conditions is possible. Additionally, the climate may get drier or more humid. These changes influence the physical and chemical behaviour of radionuclides in the top soil layers and their transport through the food chain, as well as the agricultural and dietary habits of the exposed group.

The annual average temperature varied by approximately 10–15°C during this time period [2, 21]. To mirror these changes, 9 climate reference stations in Europe and North Africa were selected with the same variety in temperature and humidity. Eight of those reference sites form a matrix with the German reference site as the ninth central element. From this center, the climate can change to all conceivably realistic temperature and humidity directions relative to current conditions. This is necessary, since the assessment has to be done over a time scale of up to one million years. During such long times, climate changes need to be taken into account [22].

Two scenarios are assumed for most of the reference sites, defined by the geosphere-biosphere interface of groundwater. In the first scenario “rising groundwater” the groundwater table is high enough to provide all the water needed for agriculture directly. Soil humidity is regulated by a drainage system. In case of the contamination of the groundwater with radionuclides, a balance between the contamination in soil and water forms quickly. This scenario is mostly used for wetland and river floodplain soils. It is assumed that for the dry reference sites the groundwater level will be too low to use this scenario.

In the second scenario “well” groundwater enters the biosphere as well water. It is assumed that water deficits of agriculture are balanced by irrigation with well water. The well water is also used as drinking water for humans and animals. Contamination can also accumulate in standing groundwater discharge systems used for fish breeding.

Four basic soil types sand, loam, clay and organic soils are included into the model to represent different possible locations and conditions for pasture or arable land. For these basic soil types, parameters for different radionuclides can be derived from the literature [9, 23].

For every biosphere model, a set of nuclide-specific dose conversion factors are determined. They quantify the mean total annual dose to a self-sustaining population. These Biosphere Dose Conversion Factors (BDCF with the unit [mSv/a per Bq/l]) are the endpoints of the model. By the analysis of the BDCFs the possibility of grouping different biosphere models into similar groups with similar exposition, as defined by BDCF, is explored. The typical biosphere models identified in the modular approach may be used as a basis for radioprotection regulation. Together with modelled radionuclide concentrations in ground water, these BDCF can be used to calculate annual doses to the exposed group.

Model development starts with the identification of important Features, Events and Processes (FEP) According to a list developed by the BIOMASS project [1]. The FEP list is discussed together with the interaction matrix and mathematical formulation of the model described in Section I.2 of Appendix I and presented in the appendix. In the following sections, the transfer of the FEP list into a model is discussed.

In Section I.3 of Appendix I the selection of the different climate reference stations following the Köppen/Geiger climate classification is discussed. The different climatic conditions at the reference sites are important for the agriculture practiced at those sites. Of special importance is the water deficit that influences the irrigation needs.

The climate and agricultural practices influence the amount and type of food and drinking water consumed by the self-sustaining population (Section I.4 of Appendix I). In Section I.5.1 of Appendix I BDCF for the different reference regions, soils and age groups are presented. A comparison between these BDCF and results from other modelling approaches are done in Section I.5.2 of Appendix I.

I.2. MODEL DESCRIPTION

I.2.1. FEP list

The biosphere model was developed after screening of the biosphere FEP list established in the BIOMASS project [1]. The results of the screening exercise are shown in Table 14 which is given at the end of this Appendix. Other relevant data are provided in Tables 15–27 which are also located at the end of this Appendix. In the following section the single FEPs are presented.

I.2.1.1. Assessment context

Purpose of the assessment is the evaluation of suitable regions for the construction of a final repository for high level radioactive waste in Germany and an assessment of the impact of climate change during the storage time frame. For this purpose a range of BDCFs for relevant radionuclides and climate reference regions are calculated. With the BDCFs annual individual doses for a self-sustaining population living in the repository area may be quantified.

A number of pathways for radionuclides in the biosphere is analyzed which include the movement of radionuclides through the food chain to a human population. The model development has to cover all relevant factors in adequate detail. At the same time the model should be clearly laid out and user-friendly, to enable assessment and use by third parties.

The models consider material fluxes in the biosphere, especially in agriculture and open water bodies, which may be contaminated by an interface to the groundwater body. For the calculation of the BDCF a standard activity concentration of 1 Bq/l groundwater is assumed. The geosphere-biosphere interface is either a “well” scenario for the abstraction of drinking and irrigation water from a well, or in the case of a high groundwater table a “rising groundwater” scenario were capillary rise of the groundwater directly influences top soil layers.

The time frame is one million years, to allow for a long term storage safety assessment. Due to the long time frame, potential changes in climate have to be accounted for, which may influence on-site parameters pertaining for the biosphere.

I.2.1.2. Biosphere system features

In the first step of the development of biosphere models the current climatic conditions have to be defined, which are characterized mostly by temperature and precipitation. Then changes in climate may be presented by the use of 8 climate reference sites. For this purpose, 8 existing climate stations were selected, representing all realistically possible climate changes. Starting with the current climate at the German reference site, possible changes to higher or lower average temperatures or higher and lower precipitation are possible (see Section I.3 of Appendix I).

Current food consumption rates and agricultural habits are determined for the different reference climates. It is assumed, that the agricultural habits and food consumption rates of self-sustaining populations adapt to climate changes (see Section I.4 of Appendix I). The climate changes result in changes in the systems of exchange like agricultural land, pastures and water bodies. Changes of soil activity concentration determine the activity concentration in plants, animals and humans.

I.2.1.3. Biosphere events and processes

Climate change is the driving force for changes in the biosphere. Variations in temperature and humidity determine the physical and chemical properties of radionuclides in soil. Corresponding changes in the transport of radionuclides through the food chain from plants to animals and humans must be considered. Human exposure also depends on agricultural practice and dietary habits of the self-sustaining population.

Internal exposure may be caused by inhalation of air-borne aerosols. Finally, external exposition from contact with contaminated soil is integrated into the model.

Subsurface water is the main pathway of radionuclides. The water enters the biosphere either by a high groundwater table, or by a well. Radionuclides move through the system either solved in water or adsorbed to soil or sediment particles. Two different types of agricultural soils are modelled, pasture and arable land. Both include sand, loam, clay and organic soil. Since the population in the model is unaware of the contamination, no countermeasures against the effects of contamination are taken by this community.

I.2.1.4. Human exposure features, events and processes

Human habits are mostly assessed in the context of agricultural practice and diet (see Section I.4 of Appendix I). Resources used from the contaminated area include drinking water, irrigation water and food produced from plants and animals. For this purpose agriculturally grown food as well as gathered food like fish, berries, mushrooms or reindeer in the tundra climate regions are included.

I.2.2. Interaction matrix of the model

The long term security assessment has a time frame of 1 million years and includes the distribution of radionuclides from the geosphere-biosphere interface to a human self-supporting group. The group is defined as a small self-sustaining subsistence community at a site potentially contaminated by radionuclides discharged from the repository. Since the discharge of radionuclides and their movement through the geosphere is not part of this model, a generic contamination 1 Bq/l of groundwater with the relevant radionuclides is assumed as source. As an endpoint, a BDCF for a human population is calculated for every modelled radionuclide. When the radionuclide concentrations in groundwater are known, annual doses to the exposed group can be calculated.

This is done for 9 climate reference sites in Europe and northern Africa. These sites represent potential changes of agricultural and dietary habits of a human population as well as changes in soil chemistry and radionuclide behaviour in soil due to climate change.

For every reference site 4 basic soil types sand, loam, clay and organic soil are modelled. This is necessary, because most parameters for radionuclide movement in the biosphere present in the literature are for these basic soil types [9, 23]. The mathematical equations were derived from the literature [24] and incorporated into the ECOLEGO modelling software (FACILIA, Stockholm Sweden).

In Table 1 an interaction matrix of the radionuclide flow in the model is presented. The compartments and expressions are marked in gray in the central diagonal, radionuclide fluxes are of center. The equation numbers for the radionuclide fluxes are given in brackets and discussed in the next section.

TABLE 1. INTERACTION MATRIX OF THE MODEL

Groundwater	Treatment (12)	Irrigation (9a)		Foliar uptake (3, 4, 5)				
	Fresh water				Drinking water (13)	Drinking water (18)	Sedimentation (16)	
		Soil	Dust formation (20)	Root uptake (11)		External exposure (23)		Leaching (9a)
			Air			Inhalation (21)		
				Plants	Feeding (13)	Food (18)		
					Animals	Food (18)		
						Humans		
							Sediment	
								Sink

NOTE: The numbers of the equation discussed in the next sub-chapter are given in brackets.

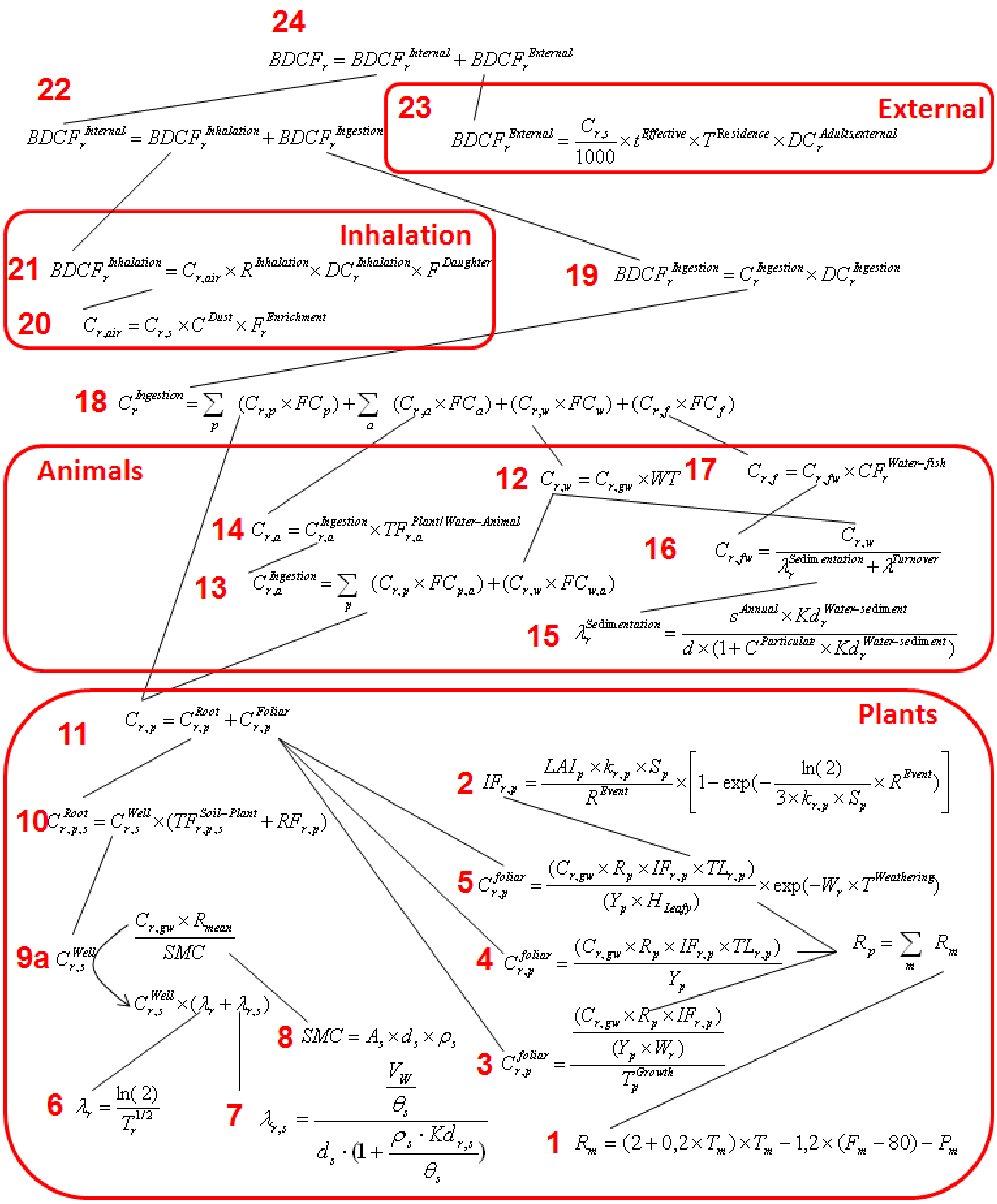


FIG. 1. Overview of the well scenario. The red numbers represent the number of the equations described in this section. The rising groundwater scenario does not include foliar uptake (3, 4, 5), and uses another equation for the calculation of activity concentration in soil (9b) instead of the one shown here (9a).

I.2.3. Mathematical description of the model

In this section, the mathematical basics for the model are described. An overview over the equations for the well scenario is given in the interaction matrix Table 1 and Figure 1. Most of the equations are used for both scenarios, rising groundwater (RGW) and “Well”. Only the soil and plant model shows some differences between “Well” and “RGW”. The activity concentration in soil is calculated with an alternative equation in the rising groundwater model, and there is no contribution of leaf uptake to the activity concentration in plants. In the model 1 litre of water is assumed to have a weight of 1 kilogram to simplify unit calculation.

Radionuclides are transported from the repository to the biosphere dissolved in groundwater. Rainfall is the other source of water for agricultural product consumption; the remaining water deficit is calculated from existing climate data.

The water demand for effective agriculture is calculated on a monthly basis by the following equation [25]:

$$R_m = (2 + 0{,}2 \times T_m) \times T_m - 1{,}2 \times (F_m - 80) - P_m \tag{1}$$

where:

R_m	is the irrigation in month m [kg/m^2];
T_m	is the average temperature in month m [°C];
F_m	is the average humidity in month m [%];
P_m	is the average precipitation in month m [mm].

To calculate the yearly irrigation demand for every plant R_p, the water deficits of the cultivation month of the corresponding plant type are added. A negative water demand makes no contribution and is set to 0. For the calculation of the activity concentration in soil, the average irrigation R_{Mean} is calculated from the mean of all plant specific irrigation values (R_p). This is necessary because the same plants will not be planted in the same soil over longer periods of time, resulting in a variation of the irrigation volume from year to year.

With this water deficit, the activity concentration uptake of plants can be calculated. The activity concentration uptake is split into two pathways for the “well” scenario, foliar activity concentration uptake $C_{r,p}^{foliar}$ and root activity concentration uptake $C_{r,p,s}^{Root}$. For the “RGW” scenario only root uptake is relevant.

For foliar uptake an interception factor has to be calculated, since a certain amount of radionuclides is retained by the foliage of plants with every irrigation event. The interception factor is calculated by the following equation [26]:

$$IF_{r,p} = \frac{LAI_p \times k_{r,p} \times S_p}{R^{Event}} \times \left[1 - \exp(-\frac{\ln(2)}{3 \times k_{r,p} \times S_p} \times R^{Event}) \right] \tag{2}$$

where:

$IF_{r,p}$	is the interception factor of radionuclide r for plant p;
LAI_p	is the leaf area index of plant p [m^2/m^2];
$k_{r,p}$	is the water storage capacity of the foliage of plant p [mm];

S_p	is the retention factor for nuclide r and plant p;
R^{Event}	is the amount of irrigation per irrigation event for plant p [mm].

For the retention factor a mean value of 0.2 is used for grass, cereals and maize [27] and a value of 0.3 for potatoes, leafy and fruit vegetables [28]. The leaf area index is changing over the growing period of the plant, since the leaf area of the plant is increasing compared to the area of soil until maturation average values are used in the model. For potatoes a value of 4, for all other plants a value of 5 is used [28].

For the foliar activity concentration uptake three different equations are used for different plant types, Equation (3) for grass and maize, Equation (4) for cereals, potatoes, fruit and fruit vegetables and Equation (5) for leafy vegetables:

$$C_{r,p}^{foliar} = \frac{\dfrac{(C_{r,gw} \times R_p \times IF_{r,p})}{(Y_p \times W_r)}}{T_p^{Growth}} \tag{3}$$

$$C_{r,p}^{foliar} = \frac{(C_{r,gw} \times R_p \times IF_{r,p} \times TL_{r,p})}{Y_p} \tag{4}$$

$$C_{r,p}^{foliar} = \frac{(C_{r,gw} \times R_p \times IF_{r,p} \times TL_{r,p})}{(Y_p \times H^{Leafy})} \times \exp(-W_r \times T^{Weathering}) \tag{5}$$

where:

$C_{r,gw}$	is the activity concentration in groundwater [Bq/kg];
$C_{r,p}^{foliar}$	is the foliar uptake of nuclide r for plant p [Bq/kg];
$IF_{r,p}$	is the interception factor of nuclide r for plant p;
H^{Leafy}	is the harvests of leafy vegetables [1/a];
R_p	is the irrigation requirement for plant p [kg/m^2 a];
$TL_{r,p}$	is the translocation factor nuclide r for plant p;
T_p^{Growth}	is the growing period of plant p [d];
W_r	is the weathering rate constant [1/d];
$T^{Weathering}$	is the minimal weathering time [d];
Y_p	is the yield of plant p [kg/m^2 a].

For the activity concentration of radionuclides in soil in the well scenario, the decay constant:

$$\lambda_r = \frac{\ln(2)}{T_r^{1/2}} \tag{6}$$

for each radionuclide is needed, where:

$T_r^{1/2}$	is the half-life of radionuclide r [a];
λ_r	is the decay constant of radionuclide r [1/a].

The migration factor describes leaching of radionuclides from top soil layers over time and determines the activity concentration in the upper soil. If a constant inflow of radionuclides by irrigation with contaminated groundwater is assumed, a balance of inflow and leaching of radionuclides will develop during several hundreds to thousand years depending on the nuclide-specific migration factor. The migration factor is calculated with the following equation [29]:

$$\lambda_{r,s} = \frac{\frac{V_W}{\theta_s}}{d_s \cdot (1 + \frac{\rho_s \cdot Kd_{r,s}}{\theta_s})} \tag{7}$$

where:

$\lambda_{r,s}$	is the migration rate for radionuclide r in soil s [1/a];
V_w	is the infiltration rate of water in soil [m/a];
θ_s	is the volumetric water content of soil s [t/m^3];
d_s	is the depth of soil s [m];
ρ_s	is the bulk density of soil s [t/m^3];
$Kd_{r,s}$	is the distribution coefficient radionuclide r and soil s [l/kg].

Another parameter is the soil mass constant (SMC) per square meter:

$$SMC = A_s \times d_s \times \rho_s \tag{8}$$

where:

A_s	is the area [m^2];
d_s	is the thickness of soil layer, 0.25 m for arable land and 0.1 m for pasture [m];
ρ_s	is the bulk density of soil [t/m^3];
SMC	is the soil mass constant per square meter [t].

In order to calculate the root uptake of radionuclides into plants the activity concentration in soil has to be calculated. For the two different scenarios two different equations are used, Equation (9a) for the well scenario and Equation (9b) for the rising groundwater scenario. Equation (9a) assumes a steady input of activity concentration by sprinkling irrigation and an output dependent on the decay of radionuclides and leaching by migration into deeper soil layers. Equation (9b) assumes a balance between groundwater and soil, depending on the distribution coefficient of radionuclides in water and soil. This balance for the rising ground water scenario is reached within 1 year in the model and no irrigation is necessary. The concentration of radionuclides in soil is included into the model as a compartment for the well scenario, Equation (9a). A certain amount of activity concentration is introduced into the compartment every year by irrigation, and a certain amount leaves the compartment by decay and migration to a sink, represented by the deeper soil layers. A balance is reached after a certain time, depending on the radio nuclide migration parameter between 100–1000 years after the start of the model. Some of the parameters used are specific for different soil types (s) like sand, loam clay and organic. In every run of the model one of those soil types is modelled:

$$\frac{C_{r,gw} \times R_{mean}}{SMC} \xrightarrow{\text{inflow}} C_{r,s}^{Well} \xrightarrow{\text{outflow}} C_{r,s}^{Well} \times (\lambda_r + \lambda_{r,s}) \tag{9a}$$

$$C_{r,s}^{RGW} = C_{r,gw} \times Kd_{r,s} \tag{9b}$$

where:

C_r^{GW}	is the activity concentration in groundwater [Bq/kg];
$C_{r,s}^{Well}$	is the activity concentration of radionuclide r in soil s for well scenario [Bq/kg];
$C_{r,s}^{RGW}$	is the activity concentration of radionuclide r in soil s for RGW scenario [Bq/kg];
$Kd_{r,s}$	is the distribution coefficient soil-water for radionuclide r and soil s [l/kg];
λ_r	is the decay constant of radionuclide r [1/a];
$\lambda_{r,s}$	is the migration rate for radionuclide r in soil s [1/a];
R_{mean}	is the mean irrigation requirement [kg/m^2 a];
SMC	is the soil mass constant [kg/m$_2$].

The most important parameter for the calculation of root uptake is the transfer factor from soil to plant. Transfer factors are given in the literature for different soil types [23]. Different transfer factors were used for subtropical, temperate and boreal climate regions. When the transfer factors were given for plant dry mass, they were recalculated for plant wet mass.

The root uptake is calculated with the same equation for all plants:

$$C_{r,p}^{Root} = C_{r,s} \times (TF_{r,p,s}^{Soil-Plant} + RF_{r,p}) \tag{10}$$

where:

$C_{r,s}$	is the concentration of radionuclide r in soil s for well or rising groundwater [Bq/kg];
$C_{r,p}^{Root}$	is the root uptake of nuclide r for plant p in soil s [Bq/kg];
$RF_{r,ü}$	is the resuspension factor for nuclide r and plant p;
$TF_{r,p,s}^{Soil-Plant}$	is the transfer factor for nuclide r, plant p and soil s.

The radionuclide uptake into plants is calculated by adding a foliar uptake to the root uptake for the well scenario, Equation (10). In the rising groundwater scenario the total activity concentration in plants is equal to the activity uptake over the roots, Equation (9b), since the water demand of a plant is met with groundwater and not with sprinkling irrigation:

$$C_{r,p} = C_{r,p,s}^{Root} + C_{r,p}^{Foliar} \tag{11}$$

where:

$C_{r,p}$	is the total activity concentration of radionuclide r in plant p [Bq/kg];
$C_{r,p}^{Root}$	is the root uptake of nuclide r for plant p in soil s [Bq/kg];
$C_{r,p}^{foliar}$	is the foliar uptake of nuclide r for plant p [Bq/kg].

Well water used as drinking water for animals or humans may be treated in waste water treatment plants to remove contaminants. In this model we assume that water is not treated, but the parameter for water treatment (WT) allows the inclusion of treatment if necessary:

$$C_{r,w} = C_{r,gw} \times WT \tag{12}$$

where:

$C_{r,gw}$ is the activity concentration in groundwater [Bq/kg];

$C_{r,w}$ is the activity concentration in treated water [Bq/kg];

WT is the water treatment constant, at the moment 1 for no treatment.

The activity uptake in domestic animals like cows, pigs and lamb relevant for the production of beef, milk, pork and mutton is calculated by adding the activity concentration of ingested food plants and water:

$$C_{r,a}^{Ingestion} = \sum_{p} (C_{r,p} \times FC_{p,a}) + (C_{r,w} \times FC_{w,a}) \tag{13}$$

where:

$C_{r,a}^{Ingestion}$ is the total daily activity ingestion of radionuclide r for animal a [Bq/d];

$C_{r,p}$ is the total activity concentration of radionuclide r in plant p [Bq/kg];

$C_{r,w}$ is the activity concentration in treated water [Bq/kg];

$FC_{p,a}$ is the uptake of plant food of plant p by animal a [kg/d];

$FC_{w,a}$ is the uptake of drinking water by animal a [kg/d].

To calculate the total activity uptake Equation (13) is used. Here the animals take up activity concentration for 1 year and then the animal products are consumed by humans. This may be a simplification for two reasons. Firstly, some animals may live longer than 1 year. Secondly, activity concentration is also excreted by animals. Nevertheless, it is assumed that the calculation represents the activity concentration in animal products, since those caveats inherently influenced the empirical derivation of the transfer factors from plant to animal:

$$C_{r,a} = C_{r,a}^{Ingestion} \times TF_{r,a}^{Plant/Water-Animal} \tag{14}$$

where:

$C_{r,a}$ is the total activity concentration of radionuclide r in animal product a [Bq/kg];

$C_{r,a}^{Ingestion}$ is the total daily activity ingestion of radionuclide r for animal a [Bq/d];

$TF_{r,a}^{Plant/Water-Animal}$ is the transfer factor of nuclide r from plants and water to animal product a.

For the calculation of activity concentration in freshwater fish, the activity concentration in a fresh water body, including radionuclides in sediments, has to be determined. Therefore, the annual sedimentation rate has to be calculated:

$$\lambda_r^{Sedimentation} = \frac{s^{Annual} \times Kd_r^{Water-sediment}}{d \times (1 + C^{Particulate} \times Kd_r^{Water-sediment})} \tag{15}$$

where:

$C^{Particulate}$ is the particulate concentration, in the model 0.1 [kg/m^3];
d is the depth of water body, in the model 3 [m];
$Kd_r^{Water-sediment}$ is the Kd value water sediment for radionuclide r [m^3/kg];
$\lambda_r^{Sedimentation}$ is the sedimentation rate for radionuclide r [1/a];
s^{Annual} is the annual sedimentation, in the model 5 [kg/m^{2}a].

Then the activity concentration in freshwater is calculated:

$$C_{r,fw} = \frac{C_{r,w}}{\lambda_r^{Sedimentation} + \lambda^{Turnover}} \tag{16}$$

where:

$C_{r,w}$ is the activity concentration in treated water [Bq/kg];
$C_{r,fw}$ is the activity concentration in freshwater water [Bq/kg];
$\lambda_r^{Sedimentation}$ is the sedimentation rate for radionuclide r [1/a];
$\lambda^{Turnover}$ is the turnover rate, 2 [1/a].

With the activity concentration in freshwater known, the activity concentration uptake of freshwater fish can be calculated:

$$C_{r,f} = C_{r,fw} \times CF_r^{Water-fish} \tag{17}$$

where:

$C_{r,f}$ is the activity concentration of radionuclide r in freshwater fish [Bq/kg];
$C_{r,fw}$ is the activity concentration in freshwater water [Bq/kg];
$CF_r^{Water-fish}$ is the concentration factor water-fish for radionuclide r.

With the knowledge about specific human diets in the different reference sites (see Section 4) the activity concentration ingestion for every radionuclide can be calculated from the activity concentration and consumption rates of the food types:

$$C_r^{Ingestion} = \sum_p (C_{r,p} \times FC_p) + \sum_a (C_{r,a} \times FC_a) + (C_{r,w} \times FC_w) + (C_{r,f} \times FC_f) \tag{18}$$

where:

$C_r^{Ingestion}$ is the activity concentration ingestion human [Bq/a];
$C_{r,a}$ is the total activity concentration of radionuclide r in animal product a [Bq/kg];
$C_{r,f}$ is the activity concentration of radionuclide r in freshwater fish [Bq/kg];
$C_{r,p}$ is the total activity concentration of radionuclide r in plant p [Bq/kg];
$C_{r,w}$ is the activity concentration in treated water [Bq/kg];
FC_a is the consumption rate of animal product a [kg/a];
FC_f is the consumption rate of fish [kg/a];

FC_p is the consumption rate of plant product p [kg/a];

FC_w is the consumption rate of drinking water [kg/a].

With the ingested activity concentration and dose conversion factors for ingested radionuclides the biosphere dose conversion factor for ingested radionuclides can be calculated:

$$BDCF_r^{Ingestion} = C_r^{Ingestion} \times DC_r^{Ingestion} \tag{19}$$

where:

$BDCF_r^{Ingestion}$ is the ingestion biosphere dose conversion factor for nuclide r [Sv/a];

$C_r^{Ingestion}$ is the annual activity ingestion human [Bq/a];

$DC_r^{Ingestion}$ is the ingestion dose conversion factor for radionuclide r [Sv/Bq].

In addition to the ingestion of radionuclides over the food chain, the population is also exposed to inhalation of activity concentration due to the inhalation of contaminated soil. The concentration of radionuclides in air is dependent on the dust content. The dust concentration in the air tends to be higher in arid climates, compared to humid climates:

$$C_{r,air} = C_{r,s} \times C^{Dust} \times F_r^{Enrichment} \tag{20}$$

where:

$C_{r,air}$ is the activity concentration of radionuclide r in air [Bq/l];

$C_{r,s}$ is the activity concentration of radionuclide r in soil s for well or rising groundwater [Bq/kg];

C^{Dust} is the dust concentration in air [µg/m^3];

$F_r^{Enrichment}$ is the enrichment factor for radionuclide r.

Now the biosphere dose conversion factor pertaining to the inhalation of different radionuclides can be calculated:

$$BDCF_r^{Inhalation} = C_{r,air} \times R^{Inhalation} \times DC_r^{Inhalation} \times F^{Daughter} \tag{21}$$

where:

$BDCF_r^{Inhalation}$ is the inhalation biosphere dose conversion factor for radionuclide r [Bq/a];

$C_{r,air}$ is the activity concentration of radionuclide r in air [Bq/l];

$R^{Inhalation}$ is the inhalation rate [m^3/a];

$DC_r^{Inhalation}$ is the dose conversion coefficient inhalation [Sv/Bq];

$F^{Daughter}$ is the Factor for Daughter nuclides.

The ingestion biosphere dose conversion factor and the inhalation biosphere dose conversion factor are then added to get the internal biosphere dose conversion factor:

$$BDCF_r^{Internal} = BDCF_r^{Inhalation} + BDCF_r^{Ingestion} \tag{22}$$

where:

$BDCF_r^{Inhalation}$ is the inhalation biosphere dose conversion factor for radionuclide r [Bq/a];
$BDCF_r^{Ingestion}$ is the ingestion biosphere dose conversion factor for radionuclide r [Bq/a];
$BDCF_r^{Internal}$ is the internal biosphere dose conversion factor for radionuclide r [Bq/a].

Since the self-supporting group is living and working on potentially contaminated land, a biosphere dose conversion factor for external exposition to activity concentration was integrated into the model:

$$BDCF_r^{External} = \frac{C_{r,s}}{1000} \times t^{Effective} \times T^{Residence} \times DC_r^{Adults,external} \quad (23)$$

where:

$BDCF_r^{External}$ is the external biosphere dose conversion factor for radionuclide r [Sv/a];
$C_{r,s}$ is the activity concentration of radionuclide r in soil s for well or rising groundwater [Bq/kg];
$DC_r^{Adults,external}$ is the external dose conversion factor for adults and radionuclide r [Sv/Bq];
$T^{Residence}$ is the residence time on contaminated land [h/a];
$t^{Effective}$ is the effective thickness of the soil layer that contributes to external exposure from radionuclide r in soil [m].

By adding the internal and external biosphere dose conversion factors the total biosphere dose conversion factor can be calculated. This BDCF is the endpoint of the model.

$$BDCF_r = BDCF_r^{Internal} + BDCF_r^{External} \quad (24)$$

$BDCF^{External}$ is the external biosphere dose conversion factor for radionuclide r [Sv/a];
$BDCF_r^{Internal}$ is the internal biosphere dose conversion factor for radionuclide r [Sv/a];
$BDCF_r$ is the total biosphere dose conversion factor for radionuclide r [Sv/a].

I.3. REFERENCE SITES FOR CLIMATE CHANGE

Since the period for the long-term security assessment is one million years for regulatory reasons, the prevailing climate during this period may be derived from the climate of the last one million years. During this time several glacial and warm periods alternated in central Europe. The average annual temperature varied by 10–15°C [2, 21]. The reference stations for the climate model were selected in such a way, that they cover a similar range of temperatures as well as more humid and dry conditions compared to the reference site Magdeburg.

A matrix with the Magdeburg reference site as central point is formed, from which the climate can change in all realistically ways concerning temperature and humidity. The relevant climate data is shown in Table 2 and Figure 2 [30]. The water deficit is calculated with Equation (1) and is summarized in Figure 3.

TABLE 2. CLIMATE DATA FOR THE 9 REFERENCE STATIONS OF THE CLIMATE CHANGE MODEL [30]

Marrakesh	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
Temperature (°C)	11.6	13.2	16.0	18.3	21.3	24.8	28.7	28.8	25.5	21.4	16.3	12.3	19.9
Precipitation (mm)	28.0	29.0	32.0	31.0	17.0	7.0	2.0	3.0	10.0	21.0	28.0	33.0	241.0
Humidity (%)	77.0	73.0	70.0	65.0	60.0	58.0	53.0	53.0	57.0	61.0	65.0	66.0	63.0
Water deficit (mm)	25.7	40.6	63.2	90.6	140.3	192.0	252.5	252.9	198.7	136.2	75.7	38.7	
Rome	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
Temperature (°C)	6.9	7.7	10.8	13.9	18.1	22.1	24.7	24.5	21.1	16.4	11.7	8.5	15.6
Precipitation (mm)	76.0	88.0	77.0	72.0	63.0	48.0	14.0	22.0	70.0	128.0	116.0	106.0	874.0
Humidity (%)	77.0	73.0	71.0	70.0	67.0	62.0	58.0	59.0	66.0	72.0	77.0	79.0	69.0
Water deficit (mm)	-49.1	-52.3	-21.3	6.4	54.3	115.5	183.8	172.3	78.0	-31.8	-61.6	-73.4	
Rostow	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
Temperature (°C)	-6.3	-5.5	0.2	8.6	15.9	19.6	22.7	21.8	15.8	9.3	2.0	-3.5	8.4
Precipitation (mm)	38.0	41.0	32.0	39.0	36.0	58.0	49.0	37.0	32.0	44.0	40.0	37.0	483.0
Humidity (%)	87.0	85.0	80.0	67.0	59.0	61.0	58.0	58.0	62.0	75.0	82.0	87.0	72.0
Water deficit (mm)	-51.1	-52.0	-31.6	8.6	71.6	80.8	125.9	128.0	71.1	-2.1	-37.6	-50.0	
Valladolid	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
Temperature (°C)	3.3	5.1	8.6	11.0	14.1	18.5	21.3	20.4	17.8	12.9	7.7	4.4	12.1
Precipitation (mm)	30.0	26.0	42.0	30.0	35.0	33.0	13.0	13.0	28.0	34.0	40.0	40.0	364.0
Humidity (%)	84.0	78.0	69.0	64.0	62.0	57.0	51.0	55.0	63.0	71.0	80.0	85.0	68.0
Water deficit (mm)	-26.0	-8.2	3.2	35.4	54.6	100.1	155.1	141.0	91.4	35.9	-12.7	-33.3	
Magdeburg	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
Temperature (°C)	-0.5	-0.1	4.0	8.8	13.4	16.4	18.5	18.3	14.9	9.7	4.8	1.2	9.2
Precipitation (mm)	36.0	31.0	29.0	35.0	49.0	58.0	64.0	57.0	38.0	43.0	40.0	33.0	513.0
Humidity (%)	84.0	82.0	76.0	70.0	67.0	67.0	70.0	71.0	74.0	79.0	85.0	87.0	76.0
Water deficit (mm)	-41.8	-33.6	-13.0	10.1	29.3	44.2	53.5	57.4	43.4	-3.6	-31.8	-38.7	
Santander	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
Temperature (°C)	9.3	9.2	11.5	12.3	14.2	16.9	18.8	19.3	18.2	15.3	12.2	9.9	13.9
Precipitation (mm)	119.0	89.0	74.0	82.0	88.0	66.0	59.0	84.0	114.0	134.0	134.0	155.0	1198.0
Humidity (%)	75.0	76.0	74.0	77.0	80.0	81.0	80.0	81.0	80.0	78.0	76.0	76.0	78.0
Water deficit (mm)	-77.1	-48.9	-17.4	-23.5	-19.3	23.7	49.3	27.9	-11.4	-54.2	-75.0	-110.8	
Turku	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
Temperature (°C)	-6.1	-6.5	-3.6	2.6	8.9	13.6	17.1	15.8	11.1	5.6	1.2	-2.4	4.8
Precipitation (mm)	43.0	27.0	23.0	33.0	30.0	40.0	67.0	77.0	65.0	64.0	58.0	49.0	576.0
Humidity (%)	87.0	84.0	79.0	74.0	64.0	66.0	69.0	74.0	79.0	84.0	88.0	89.0	78.0
Water deficit (mm)	-56.2	-36.4	-26.4	-19.2	22.8	41.0	38.9	11.7	-17.0	-51.3	-64.9	-63.4	
Sodankyla	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
Temperature (°C)	-13.5	-13.0	-9.0	-2.1	4.9	11.3	14.7	12.0	6.2	-0.5	-5.8	-9.8	-0.4
Precipitation (mm)	27.0	26.0	20.0	31.0	31.0	56.0	74.0	71.0	57.0	43.0	39.0	31.0	508.0
Humidity (%)	87.0	85.0	78.0	71.0	61.0	60.0	65.0	74.0	81.0	87.0	91.0	89.0	77.0
Water deficit (mm)	-26.0	-24.2	-19.4	-23.5	6.4	16.1	16.6	-11.0	-38.1	-52.4	-57.1	-42.2	
Vardo	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
Temperature (°C)	-4.6	-5.3	-4.0	-1.0	2.7	6.2	9.3	9.8	6.8	2.4	-0.7	-3.0	1.6
Precipitation (mm)	44.0	46.0	47.0	36.0	36.0	37.0	41.0	52.0	63.0	56.0	43.0	43.0	544.0
Humidity (%)	86.0	87.0	86.0	83.0	80.0	83.0	86.0	85.0	84.0	84.0	85.0	86.0	85.0
Water deficit (mm)	-56.2	-59.4	-59.0	-41.4	-29.1	-20.5	-12.3	-19.2	-45.0	-54.8	-50.3	-54.4	

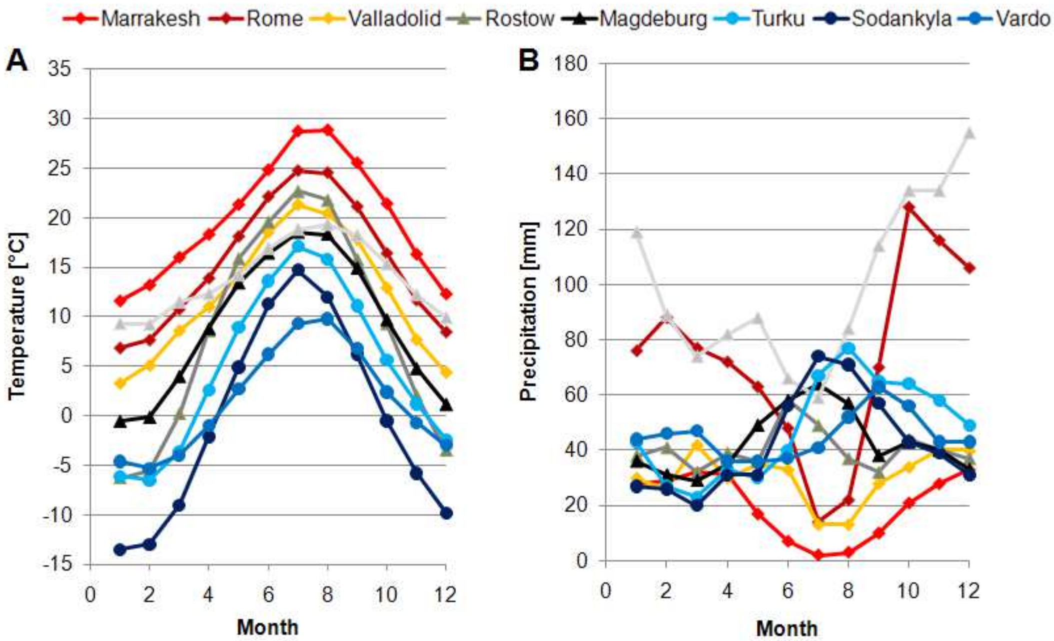


FIG. 2. (A) Average annual temperature and (B) average monthly precipitation at the reference sites for the climate change model.

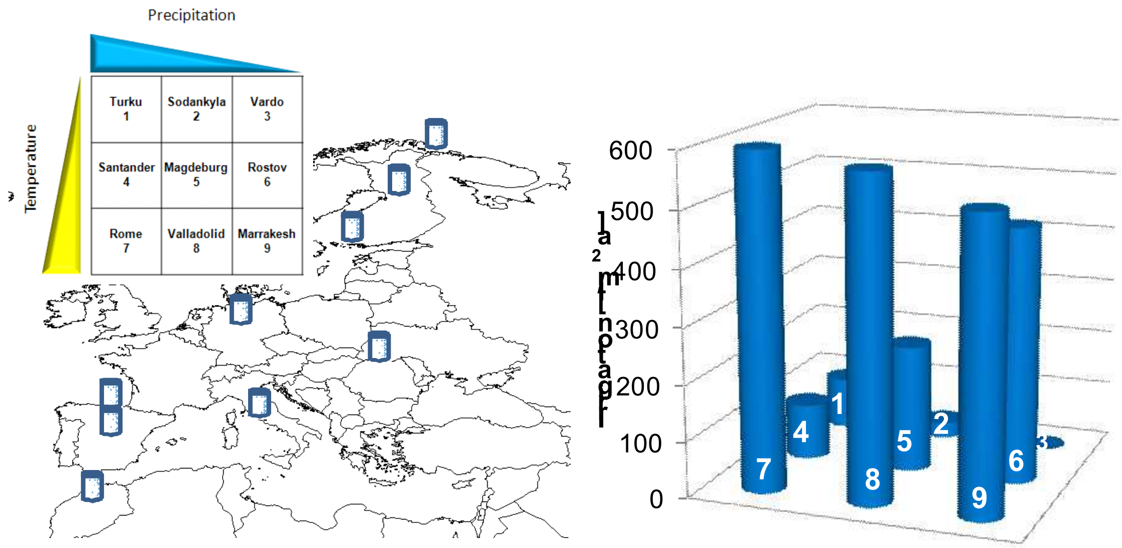


FIG. 3. Comparison of the irrigation requirements at the 9 reference sites.

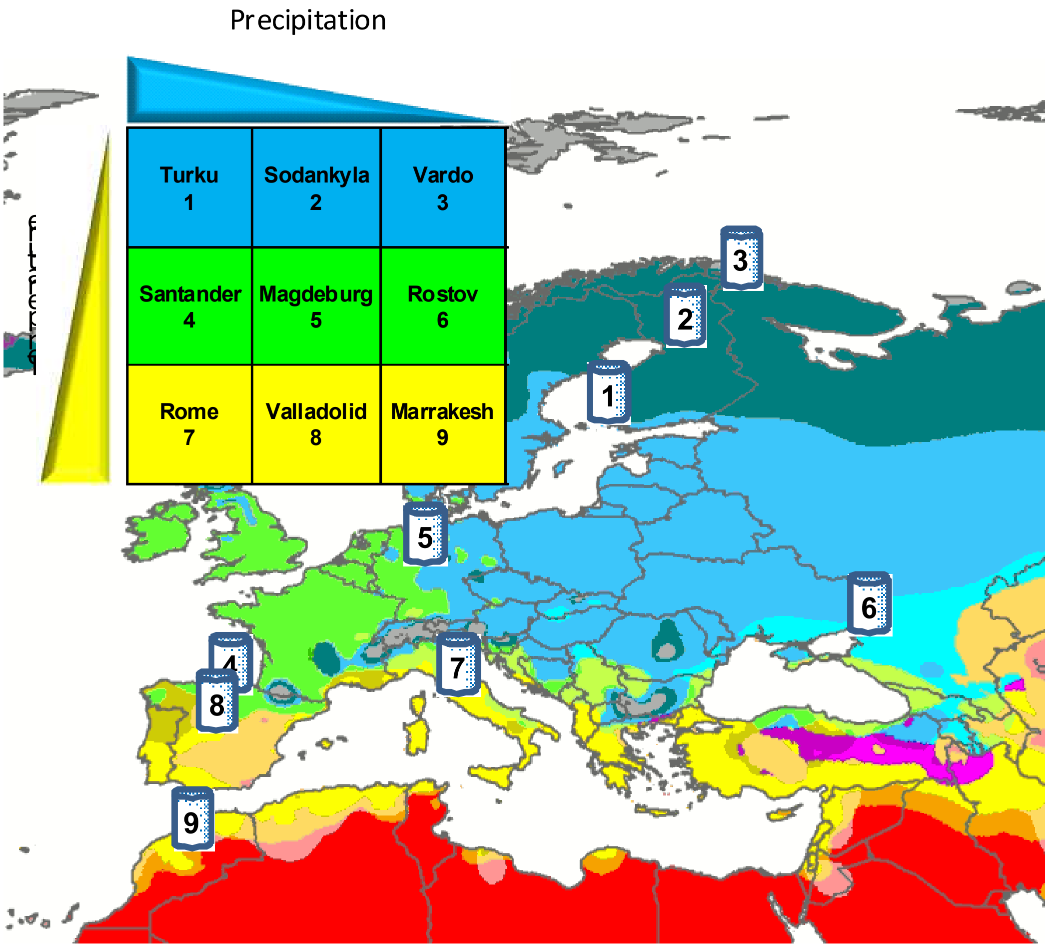


FIG. 4. The 9 reference sites for climate change classified by Köppen/Geiger [31].

For the selection of the reference sites the climate classification of Köppen/Geiger was used. This classification is based on temperature and humidity, as well as their changes during the year. The following reference climate stations were chosen, to represent all possible changes in climate from the current German situation (Figure 4).

Turku is the climate reference station at the eastern coast of Finland. Despite its coastal position it is classified as *Dfb*, warm summers, cold winters continental climate. The annual average temperature is 4.8°C, the precipitation 576 mm/m^2. In our model, Turku is used as an example for a transition to colder and more humid conditions. The agricultural water deficit has to be corrected with an average irrigation of 92 l/m^2 year.

Sodankyla is a city in central Finland, with the classification *Dfc*, continental subarctic climate with cold winters. The annual average temperature is -0.4°C, the precipitation 508 mm/m^2. In our model Sodankyla is used as an example for a climate change to colder climates. The irrigation amount is 28 l/m^2 year.

Vardo is located on island of the coast of northern Norway. Vardo is one of the few cities in Europe in the Köppen/Geiger *ET*, Tundra climate region. The annual average temperature is 1.6°C the precipitation 544 mm. Vardo is the representative climate region for a development to colder and drier climates. In spite of this, Vardo has no water deficit and it is not necessary to irrigate.

The humid, normal and dry classification of this first three northern climate stations is not always consistent. This is due to the difficulties of performing agriculture during the short summers.

Santander is located in the north of Spain at the Atlantic coast. After the Köppen/Geiger classification it is in the *Cfb* climate zone. The annual average temperature is 13.9°C, the precipitation 1198 mm/m^2. Santander is the climate station representing a change to a more humid climate. Because of the high precipitation, the irrigation requirement is just 96 l/m^2 year.

Magdeburg is the reference station representing the current German climate situation. Magdeburg has an average annual temperature of 9.2°C and a precipitation of 513 mm/m^2 and is also located in the *Cfb* climate region. Magdeburg has an irrigation requirement of 228 l/m^2 year.

Rostow is a city in the Russian Federation close to the See of Azow. It is classified as *Dfa* climate with hot continental summers. Because of the cold winters the annual average temperature is 8.4°C, the precipitation 483 mm/m^2. In spite of the cold winters, Rostow is used as the reference station for a development to warmer climates, because of its hot summers. The water deficit during the summer month has to be balanced by irrigation with 457 l/m^2 year.

Rome is classified as *Csa* with a Mediterranean climate, warm summers and an average annual temperature of 15.6°C. Because of high amounts of precipitation in the winter month the annual precipitation is 874 mm/m^2. Because of this, Rome is used as the reference station representing a development to warmer and more humid climate conditions. Nevertheless, since the most precipitation is during winter, the average irrigation requirement is 599 l/m^2 year.

Valladolid is a city in central Spain and an example for the *Csb* Köppen/Geiger classification. With an annual average temperature of 12.1°C and a precipitation of just 364 mm/m^2, Valladolid has a dry climate with warm summers, and is the reference station representing a climate change to warmer climate. Because of the low precipitation the agriculture needs irrigation amounts of 576 l/m^2 year.

Marrakesh is the only reference station outside of Europe and is located in central Morocco. Marrakesh is categorized as steppe climate *BS* in the Köppen/Geiger classification. The average annual temperature is 19.9°C, the precipitation 241 mm. Marrakesh is an example for a development to warmer and drier climates. Because of the extremely hot summers, agriculture is done in the milder winter month. The irrigation requirements are 522 l/m^2 year.

I.4. CHARACTERIZATION OF HUMAN DIET AND AGRICULTURAL FACTORS

I.4.1. Human diet

Since the largest uptake of activity concentration in our model is via food and drinking water, the dietary habits of self-supporting populations and their change due to climate change need to be assessed. Since the population is a small self-sustaining community, all food and drink is produced in the potentially contaminated area close to the repository. No import of food and drink is taken into account.

The amount of food consumed at the different reference sites are summarized in Table 26 at the end of this Appendix. For this two main sources are used [32, 33]. Unfortunately, there are quite pronounced variations in the data from different sources. For the model, the data from the German Strahlenschutzverordnung (StrlSchV) is used. Different age groups are included in the model.

For the non-German reference sites, the data from the Food and Agriculture Organization (FAO) are used, since it is one of the few sources, where the data for all countries is in one place in the same format. For the different age groups at the 8 non-German reference sites, estimates may be done based on the StrSchV values.

For the water consumption 2 litres per day (730 litres per year) are assumed for the first 5 moderate and cold climate regions, 3 litres per day (1100 litres per year) for the 4 warm reference sites.

The dietary data is used for whole countries and not the exact reference site. That may pose a problem with larger countries like Russia, where a lot of different climates can be found. Thus, the average data for a country may not adequately mirror the dietary habits at a certain reference site.

It is assumed that the dietary habits of a population adopt to climate change over longer time periods. Other socioeconomic or cultural factors, like avoiding certain foods like pork or insects, cannot be projected to the future.

Nevertheless several factors should remain stable in spite of climate or cultural changes. At a normal activity concentration level an adult needs approximately 2000 kilocalories and 2-3 litres of water per day. It can be tested if the consumption of different foods changes the BDCF, by changing the amounts of the consumed food types in the model.

The water need of humans rises with increasing temperature. In the current model it is assumed that in cold and moderate climates 2 litres, in warm climates 3 litres of water are needed per day. However it has to be kept in mind, that exertion can increase the required amount of calories and drinking water 2–4 times. Field work, which has to be done by a member of a self-sustaining community, is by definition a very exertive type of work. In colder climate regions, calorie requirements may also increase, since the body needs more calories in cold weather. This increase should also be modelled for certain cases. The following foods have been included:

- Beef, pork, lamb, poultry and sweet water fish;
- Eggs;
- Milk and milk products. Milk is not included in the water requirements;
- Leafy and fruit vegetables;
- Potatoes and roots;
- Tree fruit;
- Cereals;
- Reindeer, berries and fungi in the tundra reference site;
- All drinks are summed up as water.

Fish is only included as fresh water fish, since the contamination in sea fish should be quite low due to dilution. For this it is assumed, that rising groundwater is in direct contact with the surface water bodies in which the fish grow. Since a "worst case scenario" is used, this surface water bodies are not diluted by rain water, or cleaned by water treatment. The activity concentration is set equal to that of groundwater.

Because agriculture is difficult in colder climates and may not provide all community needs, reindeer, berries and mushrooms may be considered in tundra climates. In the tundra those food sources should be an important part of the diet of subsistence communities.

Current data for dietary habits are usually not for self-sustaining populations and are to be viewed critically. A lot of food is imported, for example the consumption of citrus foods is quite high in Germany. In self-sustaining communities in moderate and cold climates those are not available. The vitamin requirement of the self-sustaining group has to be satisfied by other mean, for example local fruit and vegetables.

I.4.2. Agricultural factors

The type and level of technology used by a self-sustaining group is an important factor concerning the model and eludes prognosis. Because of this, the agricultural practices part of the model is quite rudimentary. Four basic soil types, sand, loam, clay and organic are included, together with two types of land, pasture and arable. In addition to that two scenarios "well" and "rising groundwater" are used as geosphere-biosphere interface. A few additional points should be kept in mind nevertheless.

The higher the degree of automation and technology, the less exertive agricultural work should be. That influences the calorie and drinking water requirements of the group.

Another factor is the use of fertilizers, which is currently not included in the model. A few examples how fertilizer use may influence the activity concentration uptake are:

- At lower technological levels three field crop rotation, where arable land is used as pasture in some years, or where legumes are planted to fixate nitrogen.
- Use of manure as fertilizer may increase the activity concentration due to excreted radionuclides.
- Use of mineral fertilizer. Depending on the type, source and production different levels of activity concentration could be assumed. Fertilizer from mined potassium salts may be problematic, because the potassium mine may be close to the repository and constitute a worst case human intrusion scenario. Nitrogen fertilizer produced by the Haber-Bosch method should not be contaminated.

The most important source of activity concentration in plants is the irrigation water in the current model. The amount of irrigation water needed is depended on the climate in the month of cultivation (Table 2). It is also relevant if the plants are irrigated by surface or sprinkling irrigation. In the model sprinkling irrigation is assumed and the corresponding activity concentration intake by the leaves in addition to root uptake is modelled. Other means to intensify agriculture or safe water, like greenhouses are to manifold to include in the model.

I.5. RESULTS

I.5.1. BDCF for the 9 reference regions for climate change

As an endpoint for the assessment, a range of BDCF for different radio-nuclides and reference stations were calculated. The BDCF presented here are given for three age groups, infants, children and adults [34] and for the soil types sand, loam, clay and organic [23].

Since the model assumes a dynamic compartment for the concentration of radionuclides in soil for the well model (see Equation (9a)), the activity concentration in soil increases for a few hundred years after the start of the model until inflow and outflow of activity concentration is balance. The BDCF are calculated for the steady state after equilibrium is reached.

The total nuclide-specific BDCF is calculated by adding the BDCF for inhalation, ingestion and external exposure. The BDCF contribution of the different food types and drinking water can be analyzed. In Figure 5 an example is given for several radionuclides at the Magdeburg reference station for a sand soil and an adult age group. The contributions of the ingestion, inhalation and external exposure pathways to the BDCF are shown in Figure 6 for a selection of radionuclides.

The BDCF of selected radionuclides for sand soil and an adult population are compared in Figure 7 to highlight their dependence on the climate reference sites. For the majority of nuclides the BDCF is highest in reference sites which require the most irrigation to balance the water deficit of agricultural plants (Figure 3).

Another important factor influencing the results are the different transfer factors from soil to plant used for the subtropical, temperate and boreal climate regions, and the consumption habits of the exposed group. For radionuclides with a high contribution of the drinking water contamination to the ingestion BDCF and a high contribution of the ingestion BDCF to the total BDCF, the amount of consumed drinking water is a decisive factor. For radionuclides with a high contribution of the inhalation pathway, like Am-243, Pa-231 and Pu-239, the dust concentration in air is a critical parameter.

Note, that those BDCF are defined for a generic radionuclide contamination of 1 Bq/l in groundwater. To calculate the dose for the population, the actual activity concentration in groundwater has to be known.

The influence of different soil types on the BDCF at the German reference region is shown in Figure 8. The two soil class dependent parameters influencing the resulting BDCF are the soil Kd and the transfer factor soil to plant. For some radionuclides, like Am-243, I-129 and Pu-239, the resulting BDCF are very similar for the different soil types since a higher Kd often corresponds with a lower transfer factor. In other cases BDCF does vary between the different soil types.

BDCF for different age groups at the German reference region are shown in Figure 9. For most radionuclides, the resulting BDCF for the different age groups are relatively similar. The BDCF for all reference regions, soil types and age groups are shown in Tables 3–11.

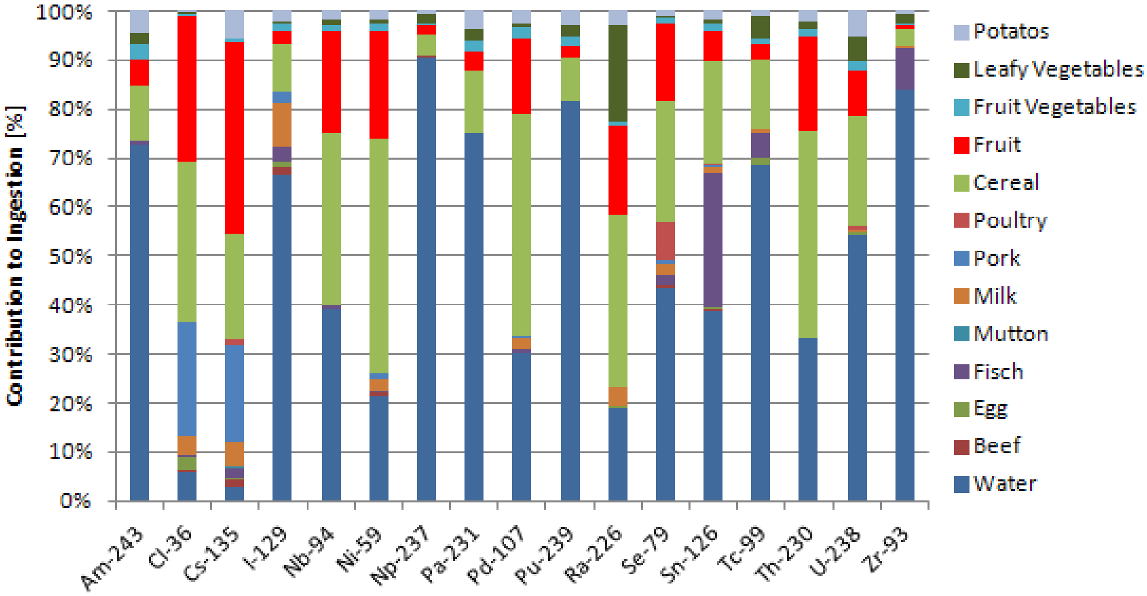


FIG. 5. Contributions from different food types and drinking water to the ingestion BDCF.

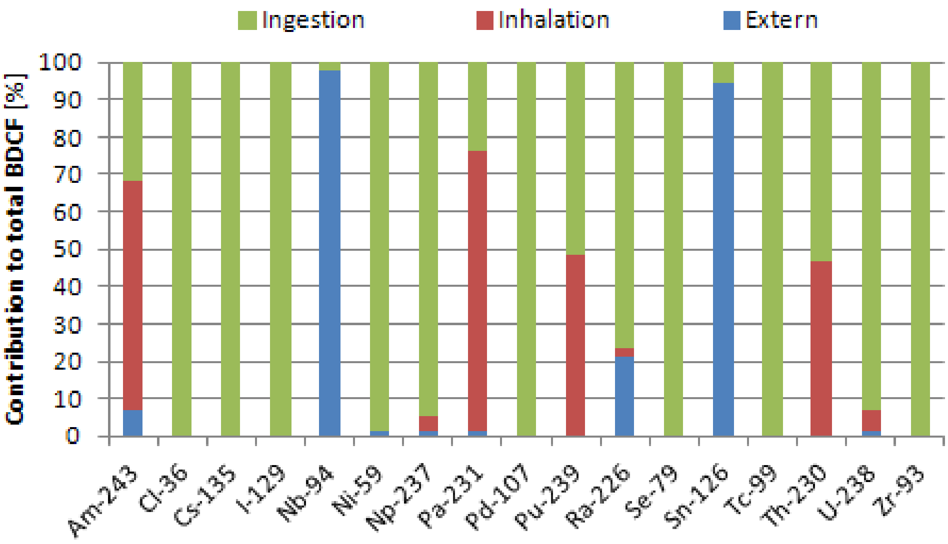


FIG. 6. Contributions of the ingestion, inhalation and external exposure pathways to the total BDCF.

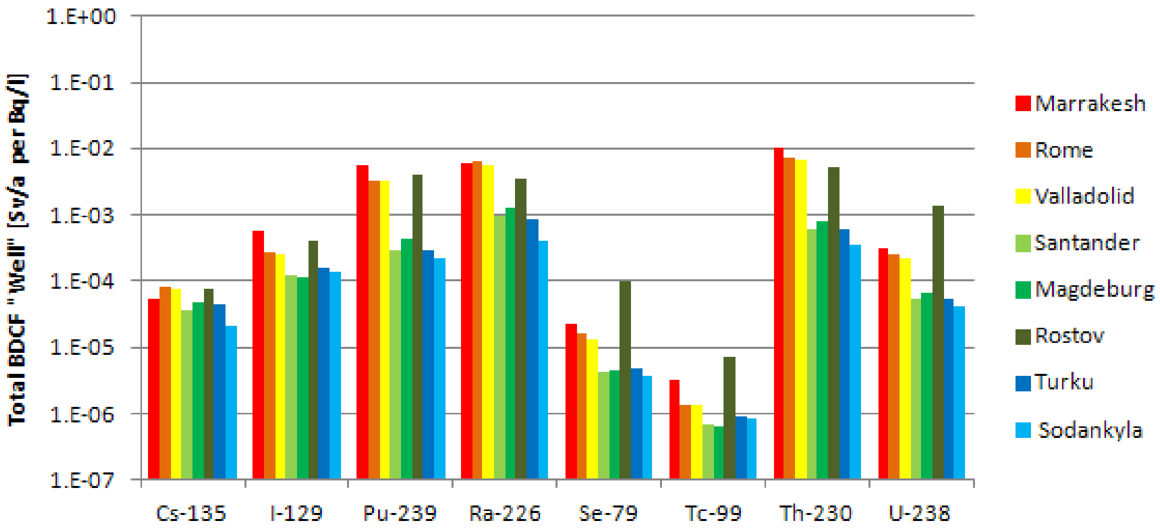


FIG. 7. Summary of selected radionuclide BDCF at different reference sites.

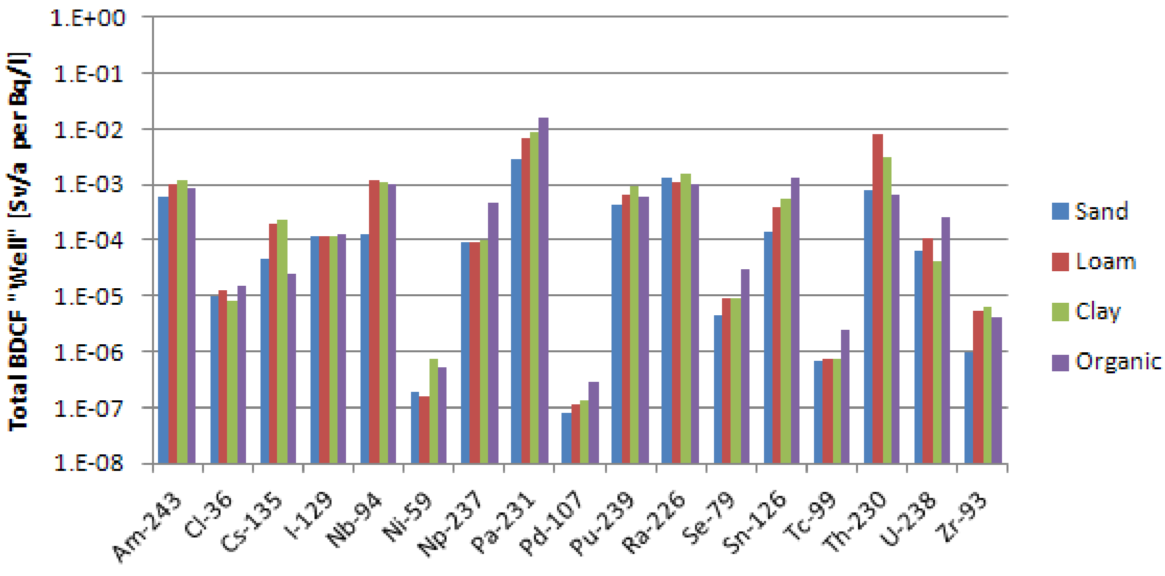


FIG. 8. Influence of different soil type on the BDCF at the Magdeburg reference region.

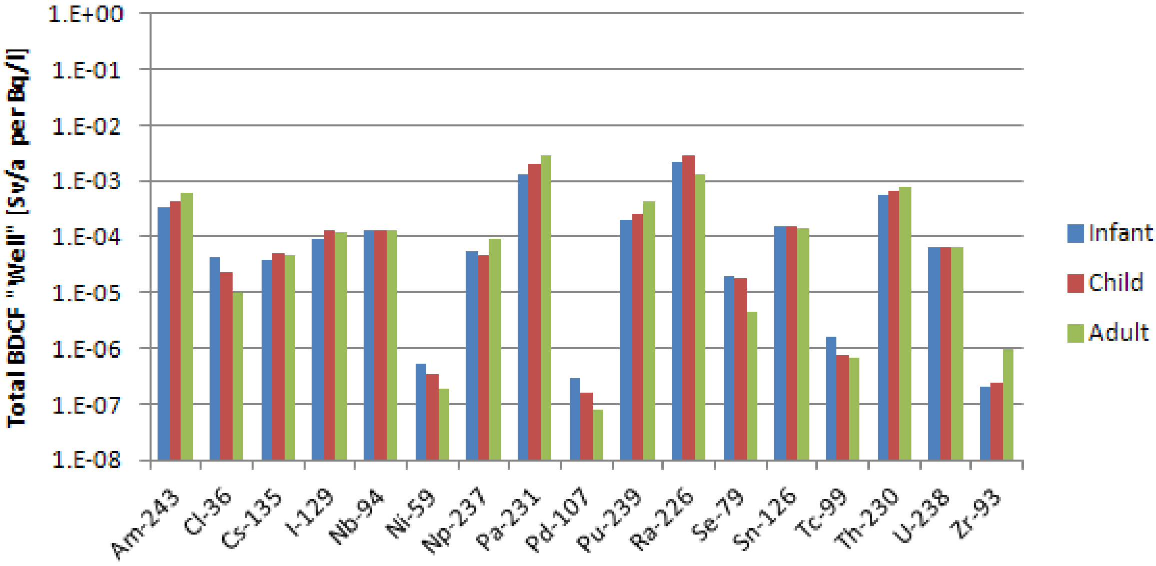


FIG. 9. Influence of age groups on the BDCF at the Magdeburg reference region.

TABLE 3. TOTAL BDCF IN SV/A PER BQ/L FOR REFERENCE REGION MARRAKESH

Source	Person	Am-243	Cl-36	Cs-135	I-129	Nb-94	Ni-59	Np-237	Pa-231	Pd-107	Pu-239	Ra-226	Se-79	Sn-126	Tc-99	Th-230	U-238	Zr-93
Sand Well	Infant	4.4E-03	1.7E-04	3.9E-05	3.6E-04	3.2E-04	3.4E-06	1.8E-04	2.1E-02	2.0E-06	2.4E-03	9.9E-03	9.6E-05	4.2E-04	7.6E-06	5.6E-03	3.3E-04	5.4E-07
	Child	7.0E-03	9.1E-05	4.8E-05	7.7E-04	3.1E-04	2.5E-06	2.1E-04	4.0E-02	1.4E-06	4.0E-03	1.4E-02	1.0E-04	4.0E-04	5.2E-06	8.3E-03	3.6E-04	8.2E-07
	Adult	9.7E-03	3.6E-05	5.3E-05	5.6E-04	3.0E-04	1.5E-06	3.1E-04	5.1E-02	7.0E-07	5.7E-03	6.0E-03	2.3E-05	3.6E-04	3.2E-06	1.0E-02	3.1E-04	2.4E-06
Sand RGW	Infant	1.4E-03	2.7E-05	7.2E-06	7.8E-05	6.6E-05	4.8E-07	7.9E-05	4.7E-03	2.5E-07	5.9E-04	1.5E-02	1.9E-05	7.7E-05	1.5E-06	1.2E-03	8.8E-05	2.6E-07
	Child	2.2E-03	1.4E-05	8.0E-06	1.0E-04	6.2E-05	2.8E-07	6.8E-05	8.4E-03	1.3E-07	8.9E-04	2.3E-02	1.6E-05	7.0E-05	6.3E-07	1.7E-03	8.6E-05	3.1E-07
	Adult	3.1E-03	6.1E-06	9.5E-06	1.3E-04	6.0E-05	1.8E-07	1.4E-04	1.1E-02	7.7E-08	1.4E-03	1.0E-02	4.8E-06	6.8E-05	7.1E-07	2.2E-03	9.5E-05	1.3E-06
Loam Well	Infant	8.4E-03	1.7E-04	8.7E-04	3.8E-04	3.0E-03	3.5E-06	2.2E-04	5.8E-02	2.7E-06	4.8E-03	7.9E-03	2.4E-04	1.1E-03	7.9E-06	7.2E-02	7.3E-04	1.7E-05
	Child	1.3E-02	1.0E-04	9.4E-04	8.0E-04	2.9E-03	2.3E-06	2.5E-04	1.1E-01	1.8E-06	8.0E-03	1.3E-02	2.4E-04	1.0E-03	5.3E-06	1.0E-01	7.9E-04	2.6E-05
	Adult	1.8E-02	4.5E-05	6.8E-04	5.7E-04	2.8E-03	1.3E-06	3.7E-04	1.4E-01	8.7E-07	1.1E-02	5.1E-03	4.5E-05	9.5E-04	3.3E-06	1.3E-01	6.3E-04	5.4E-05
Loam RGW	Infant	5.6E-03	2.6E-05	1.8E-04	8.3E-05	9.3E-04	5.2E-07	8.6E-05	1.5E-02	4.0E-07	1.2E-03	5.5E-03	4.9E-05	2.1E-04	1.6E-06	2.8E-02	1.7E-04	3.7E-06
	Child	8.9E-03	1.5E-05	1.9E-04	1.1E-04	8.9E-04	2.6E-07	7.7E-05	2.7E-02	2.2E-07	2.0E-03	9.2E-03	4.3E-05	2.0E-04	6.5E-07	4.1E-02	1.8E-04	5.4E-06
	Adult	1.2E-02	6.9E-06	1.4E-04	1.3E-04	8.6E-04	1.5E-07	1.5E-04	3.5E-02	1.1E-07	2.8E-03	4.0E-03	9.3E-06	1.9E-04	7.2E-07	5.2E-02	1.6E-04	1.2E-05
Clay Well	Infant	6.4E-03	4.8E-01	5.3E-05	3.4E-04	3.2E-03	1.8E-04	3.5E-03	6.1E-02	2.9E-05	5.5E-03	1.1E-02	1.1E-04	1.8E-03	8.3E-04	1.7E-02	6.4E-03	1.2E-05
	Child	1.1E-02	2.1E-01	8.3E-05	7.5E-04	3.0E-03	8.8E-05	3.5E-03	1.2E-01	1.3E-05	9.7E-03	1.8E-02	1.4E-04	1.7E-03	3.3E-04	2.9E-02	5.5E-03	2.1E-05
	Adult	1.5E-02	5.5E-02	1.2E-04	5.6E-04	2.9E-03	3.0E-05	3.5E-03	1.5E-01	3.7E-06	1.4E-02	7.4E-03	3.5E-05	1.6E-03	9.1E-05	3.9E-02	2.8E-03	5.5E-05
Clay RGW	Infant	1.0E-02	1.3E-05	5.2E-05	8.6E-05	8.9E-04	2.7E-06	9.7E-05	2.1E-02	5.5E-07	2.1E-03	1.8E-01	5.2E-05	3.1E-04	1.6E-06	6.8E-03	4.7E-05	4.1E-06
	Child	1.7E-02	7.3E-06	6.0E-05	1.1E-04	8.6E-04	1.6E-06	9.2E-05	4.0E-02	3.0E-07	3.5E-03	3.4E-01	4.6E-05	2.9E-04	6.5E-07	1.0E-02	4.3E-05	6.4E-06
	Adult	2.4E-02	3.6E-06	6.3E-05	1.3E-04	8.3E-04	8.3E-07	1.7E-04	5.2E-02	1.5E-07	5.1E-03	1.4E-01	9.9E-06	2.8E-04	7.2E-07	1.3E-02	6.1E-05	1.5E-05
Organic Well	Infant	6.8E-03	2.3E-04	1.9E-05	5.0E-04	2.5E-03	1.3E-05	3.5E-03	1.4E-01	6.7E-06	3.9E-03	7.1E-03	9.0E-04	3.3E-03	1.8E-05	5.1E-03	2.4E-03	1.2E-05
	Child	1.0E-02	8.7E-05	2.3E-05	8.4E-04	2.3E-03	4.0E-06	3.9E-03	2.5E-01	3.2E-06	6.3E-03	8.4E-03	5.4E-04	3.1E-03	6.7E-06	7.0E-03	2.2E-03	1.6E-05
	Adult	1.5E-02	5.5E-05	3.1E-05	6.3E-04	2.3E-03	3.1E-06	5.5E-03	3.3E-01	1.8E-06	9.0E-03	4.3E-03	1.4E-04	3.0E-03	4.4E-06	9.4E-03	2.0E-03	3.7E-05
Organic RGW	Infant	3.4E-03	4.1E-05	3.7E-06	1.1E-04	7.4E-04	2.6E-06	7.8E-04	5.2E-02	1.3E-06	1.0E-03	5.4E-03	1.9E-04	7.3E-04	3.7E-06	1.2E-03	5.4E-04	2.7E-06
	Child	5.2E-03	1.5E-05	3.5E-06	1.2E-04	7.0E-04	6.7E-07	8.5E-04	9.7E-02	5.1E-07	1.6E-03	7.2E-03	1.1E-04	6.8E-04	9.9E-07	1.6E-03	4.8E-04	3.5E-06
	Adult	7.5E-03	9.7E-06	5.7E-06	1.4E-04	6.9E-04	5.6E-07	1.3E-03	1.3E-01	3.1E-07	2.3E-03	3.7E-03	3.1E-05	6.7E-04	9.7E-07	2.2E-03	4.7E-04	8.7E-06

TABLE 4. TOTAL BDCF IN SV/A PER BQ/L FOR REFERENCE REGION ROME

Source	Person	Am-243	Cl-36	Cs-135	I-129	Nb-94	Ni-59	Np-237	Pa-231	Pd-107	Pu-239	Ra-226	Se-79	Sn-126	Tc-99	Th-230	U-238	Zr-93
Sand Well	Infant	2.7E-03	3.2E-04	8.9E-05	2.8E-04	3.7E-04	3.9E-06	1.5E-04	1.2E-02	1.8E-06	1.4E-03	1.4E-02	1.2E-04	4.3E-04	4.7E-06	4.7E-03	3.5E-04	4.3E-07
	Child	4.0E-03	1.6E-04	8.8E-05	3.8E-04	3.5E-04	2.1E-06	1.4E-04	2.2E-02	9.1E-07	2.3E-03	1.9E-02	9.7E-05	3.9E-04	2.2E-06	5.9E-03	3.4E-04	5.4E-07
	Adult	5.5E-03	5.2E-05	8.2E-05	2.7E-04	3.3E-04	9.4E-07	2.2E-04	2.9E-02	3.5E-07	3.2E-03	6.4E-03	1.7E-05	7.1E-04	1.4E-06	7.4E-03	2.5E-04	1.8E-06
Sand RGW	Infant	8.0E-04	5.0E-05	1.7E-05	1.1E-04	6.9E-05	7.1E-07	7.7E-05	2.6E-03	3.3E-07	3.6E-04	1.7E-02	2.7E-05	8.9E-05	1.8E-06	9.4E-04	9.0E-05	2.9E-07
	Child	1.2E-03	2.4E-05	1.6E-05	1.3E-04	6.3E-05	3.7E-07	6.4E-05	4.5E-03	1.5E-07	5.2E-04	2.3E-02	2.1E-05	7.5E-05	7.2E-07	1.2E-03	8.3E-05	3.4E-07
	Adult	1.7E-03	8.6E-06	1.7E-05	1.4E-04	6.0E-05	1.9E-07	1.3E-04	6.0E-03	7.9E-08	8.1E-04	9.3E-03	5.4E-06	2.3E-04	7.7E-07	1.6E-03	8.6E-05	1.4E-06
Loam Well	Infant	3.0E-03	4.4E-05	3.8E-04	1.2E-04	9.7E-04	8.9E-07	8.4E-05	7.7E-03	5.7E-07	6.9E-04	5.7E-03	7.7E-05	2.3E-04	1.9E-06	2.1E-02	1.8E-04	2.7E-06
	Child	1.3E-02	5.3E-04	2.9E-03	5.0E-04	3.9E-03	7.3E-06	3.2E-04	9.2E-02	5.1E-06	7.2E-03	1.8E-02	6.2E-04	1.3E-03	9.0E-06	1.4E-01	1.4E-03	2.4E-05
	Adult	1.0E-02	5.8E-05	1.5E-03	2.8E-04	3.1E-03	9.3E-07	2.5E-04	7.7E-02	5.3E-07	6.3E-03	5.0E-03	4.5E-05	1.6E-03	1.5E-06	9.2E-02	5.2E-04	3.5E-05
Loam RGW	Infant	5.1E-03	3.1E-04	2.1E-03	3.2E-04	3.5E-03	4.7E-06	1.8E-04	3.3E-02	3.0E-06	2.8E-03	1.0E-02	3.9E-04	1.1E-03	5.4E-06	6.6E-02	8.0E-04	1.4E-05
	Child	7.9E-03	7.4E-05	5.4E-04	1.7E-04	1.1E-03	1.3E-06	1.3E-04	2.1E-02	9.2E-07	1.7E-03	1.0E-02	1.2E-04	2.5E-04	2.8E-06	4.6E-02	3.1E-04	4.8E-06
	Adult	6.4E-03	8.8E-06	2.8E-04	1.5E-04	8.6E-04	2.0E-07	1.4E-04	1.8E-02	1.1E-07	1.6E-03	3.3E-03	1.1E-05	3.9E-04	7.8E-07	3.3E-02	1.4E-04	7.6E-06
Clay Well	Infant	6.2E-03	2.3E-04	2.8E-03	3.8E-04	3.2E-03	2.3E-05	2.4E-04	4.3E-02	4.1E-06	4.4E-03	1.5E-02	3.9E-04	1.5E-03	8.9E-06	2.3E-02	1.1E-04	1.8E-05
	Child	9.1E-03	1.1E-04	2.9E-03	4.7E-04	3.0E-03	1.1E-05	2.2E-04	7.7E-02	1.9E-06	7.0E-03	2.2E-02	3.1E-04	1.4E-03	3.9E-06	2.8E-02	9.9E-05	2.3E-05
	Adult	1.2E-02	3.7E-05	2.0E-03	3.1E-04	2.8E-03	4.5E-06	3.1E-04	9.8E-02	6.8E-07	9.6E-03	7.0E-03	4.5E-05	2.1E-03	2.4E-06	3.4E-02	9.5E-05	4.2E-05
Clay RGW	Infant	5.9E-03	2.7E-05	5.6E-04	1.3E-04	9.3E-04	4.6E-06	9.6E-05	1.2E-02	8.1E-07	1.2E-03	1.9E-01	8.4E-05	3.3E-04	2.0E-06	5.4E-03	5.0E-05	4.0E-06
	Child	8.9E-03	1.2E-05	5.9E-04	1.6E-04	8.7E-04	2.3E-06	8.2E-05	2.1E-02	3.8E-07	1.9E-03	2.9E-01	6.6E-05	3.0E-04	8.3E-07	6.8E-03	4.3E-05	4.9E-06
	Adult	1.2E-02	4.8E-06	4.0E-04	1.5E-04	8.3E-04	9.6E-07	1.5E-04	2.7E-02	1.5E-07	2.7E-03	1.1E-01	1.1E-05	5.2E-04	8.4E-07	8.4E-03	5.9E-05	9.6E-06
Organic Well	Infant	4.1E-03	4.4E-04	1.7E-04	5.8E-04	2.9E-03	2.3E-05	3.3E-03	7.8E-02	9.5E-06	2.2E-03	9.9E-03	1.6E-03	3.6E-03	5.9E-05	4.3E-03	2.8E-03	9.3E-06
	Child	4.7E-03	1.2E-04	5.0E-05	2.4E-04	8.5E-04	6.9E-06	1.3E-03	7.6E-02	3.0E-06	1.4E-03	1.0E-02	5.0E-04	8.1E-04	1.9E-05	2.0E-03	1.0E-03	3.3E-06
	Adult	8.4E-03	7.6E-05	1.5E-04	4.1E-04	2.5E-03	3.9E-06	3.8E-03	1.8E-01	1.5E-06	5.1E-03	4.3E-03	1.8E-04	4.7E-03	1.3E-05	6.6E-03	1.7E-03	2.5E-05
Organic RGW	Infant	1.8E-03	7.1E-05	3.4E-05	1.7E-04	7.8E-04	4.6E-06	7.0E-04	2.7E-02	1.8E-06	5.8E-04	6.0E-03	3.2E-04	7.5E-04	1.2E-05	9.5E-04	5.7E-04	2.0E-06
	Child	2.6E-02	7.3E-04	2.8E-04	1.2E-03	3.8E-03	5.0E-05	1.4E-02	4.1E-01	2.4E-05	1.8E-02	3.0E-02	3.7E-03	5.9E-03	9.5E-05	2.1E-02	1.1E-02	1.4E-04
	Adult	3.9E-03	1.3E-05	3.1E-05	1.7E-04	6.9E-04	8.1E-07	8.2E-04	6.4E-02	3.1E-07	1.3E-03	3.1E-03	3.6E-05	1.0E-03	3.0E-06	1.6E-03	3.8E-04	5.8E-06

TABLE 5. TOTAL BDCF IN SV/A PER BQ/L FOR REFERENCE REGION VALLADOLID

Source	Person	Am-243	Cl-36	Cs-135	I-129	Nb-94	Ni-59	Np-237	Pa-231	Pd-107	Pu-239	Ra-226	Se-79	Sn-126	Tc-99	Th-230	U-238	Zr-93
Sand Well	Infant	2.6E-03	2.2E-04	7.2E-05	2.5E-04	3.6E-04	2.7E-06	1.4E-04	1.2E-02	1.3E-06	1.4E-03	1.1E-02	8.5E-05	4.3E-04	3.9E-06	3.9E-03	2.8E-04	4.2E-07
	Child	4.1E-03	1.1E-04	7.4E-05	3.4E-04	3.5E-04	1.5E-06	1.3E-04	2.3E-02	6.5E-07	2.3E-03	1.4E-02	7.1E-05	4.0E-04	1.9E-06	5.2E-03	2.8E-04	5.2E-07
	Adult	5.6E-03	3.8E-05	7.6E-05	2.5E-04	3.4E-04	6.8E-07	2.1E-04	2.9E-02	2.7E-07	3.3E-03	5.4E-03	1.3E-05	7.0E-04	1.3E-06	6.8E-03	2.2E-04	1.8E-06
Sand RGW	Infant	7.7E-04	3.3E-05	1.3E-05	1.0E-04	6.6E-05	4.8E-07	7.5E-05	2.5E-03	2.4E-07	3.6E-04	1.4E-02	2.1E-05	8.8E-05	1.8E-06	7.7E-04	7.7E-05	3.0E-07
	Child	1.2E-03	1.6E-05	1.4E-05	1.3E-04	6.2E-05	2.5E-07	6.2E-05	4.4E-03	1.1E-07	5.1E-04	1.8E-02	1.7E-05	7.5E-05	7.3E-07	9.9E-04	7.1E-05	3.5E-07
	Adult	1.7E-03	6.3E-06	1.6E-05	1.4E-04	6.0E-05	1.5E-07	1.3E-04	5.9E-03	6.6E-08	8.1E-04	8.0E-03	4.9E-06	2.3E-04	7.9E-07	1.5E-03	8.0E-05	1.4E-06
Loam Well	Infant	5.1E-03	2.1E-04	1.4E-03	2.9E-04	3.5E-03	3.3E-06	1.7E-04	3.4E-02	2.2E-06	2.9E-03	8.2E-03	2.6E-04	1.1E-03	4.6E-06	5.4E-02	6.9E-04	1.3E-05
	Child	7.7E-03	1.1E-04	1.4E-03	3.7E-04	3.3E-03	1.6E-06	1.6E-04	6.1E-02	1.0E-06	4.5E-03	1.0E-02	2.1E-04	1.1E-03	2.0E-06	6.8E-02	6.1E-04	1.5E-05
	Adult	1.1E-02	4.4E-05	1.0E-03	2.7E-04	3.1E-03	6.8E-07	2.5E-04	7.9E-02	3.9E-07	6.4E-03	4.0E-03	3.3E-05	1.5E-03	1.4E-06	8.4E-02	4.6E-04	3.2E-05
Loam RGW	Infant	3.0E-03	2.9E-05	2.4E-04	1.1E-04	9.2E-04	6.0E-07	8.1E-05	7.6E-03	4.0E-07	6.9E-04	4.6E-03	5.3E-05	2.2E-04	1.8E-06	1.7E-02	1.5E-04	2.6E-06
	Child	4.5E-03	1.5E-05	2.5E-04	1.3E-04	8.8E-04	2.9E-07	6.7E-05	1.4E-02	1.8E-07	1.0E-03	5.9E-03	4.2E-05	2.0E-04	7.5E-07	2.2E-02	1.3E-04	2.9E-06
	Adult	6.3E-03	6.7E-06	1.9E-04	1.4E-04	8.5E-04	1.5E-07	1.4E-04	1.8E-02	8.9E-08	1.5E-03	2.6E-03	8.5E-06	3.9E-04	8.0E-07	2.9E-02	1.2E-04	6.8E-06
Clay Well	Infant	6.1E-03	1.4E-04	5.1E-04	3.0E-04	3.2E-03	1.5E-05	2.1E-04	4.3E-02	2.8E-06	4.4E-03	1.1E-02	2.6E-04	1.5E-03	4.9E-06	1.9E-02	9.5E-05	1.6E-05
	Child	9.1E-03	7.4E-05	5.0E-04	4.0E-04	3.0E-03	7.6E-06	2.0E-04	7.9E-02	1.3E-06	7.0E-03	1.5E-02	2.1E-04	1.5E-03	2.2E-06	2.4E-02	8.5E-05	1.9E-05
	Adult	1.2E-02	2.8E-05	4.8E-04	2.8E-04	2.9E-03	3.1E-06	3.0E-04	1.0E-01	4.9E-07	9.9E-03	5.3E-03	3.3E-05	2.0E-03	1.4E-06	3.1E-02	8.9E-05	3.8E-05
Clay RGW	Infant	5.7E-03	1.6E-05	1.0E-04	1.1E-04	8.9E-04	3.0E-06	9.0E-05	1.1E-02	5.5E-07	1.2E-03	1.3E-01	5.7E-05	3.2E-04	1.8E-06	4.4E-03	4.7E-05	3.3E-06
	Child	8.7E-03	8.1E-06	9.9E-05	1.4E-04	8.5E-04	1.5E-06	7.8E-05	2.0E-02	2.5E-07	1.8E-03	2.0E-01	4.5E-05	2.9E-04	7.5E-07	5.8E-03	4.0E-05	4.0E-06
	Adult	1.2E-02	3.8E-06	9.7E-05	1.5E-04	8.2E-04	6.5E-07	1.5E-04	2.6E-02	1.1E-07	2.7E-03	7.9E-02	8.9E-06	5.0E-04	8.0E-07	7.5E-03	5.8E-05	8.4E-06
Organic Well	Infant	4.1E-03	2.9E-04	3.3E-05	4.6E-04	2.9E-03	1.6E-05	3.0E-03	8.0E-02	6.5E-06	2.3E-03	8.0E-03	1.1E-03	3.7E-03	2.1E-05	3.7E-03	2.3E-03	9.2E-06
	Child	6.2E-03	1.5E-04	3.5E-05	5.9E-04	2.7E-03	7.4E-06	3.2E-03	1.5E-01	3.1E-06	3.7E-03	1.0E-02	8.5E-04	3.5E-03	8.2E-06	4.8E-03	2.1E-03	1.1E-05
	Adult	8.6E-03	5.7E-05	3.7E-05	3.5E-04	2.6E-03	2.7E-06	3.7E-03	1.9E-01	1.1E-06	5.2E-03	3.7E-03	1.2E-04	4.4E-03	3.2E-06	6.2E-03	1.5E-03	2.2E-05
Organic RGW	Infant	1.8E-03	4.6E-05	7.4E-06	1.4E-04	7.4E-04	3.0E-06	6.1E-04	2.7E-02	1.2E-06	5.8E-04	5.1E-03	2.0E-04	7.3E-04	4.8E-06	8.1E-04	4.6E-04	1.9E-06
	Child	2.7E-03	2.4E-05	7.8E-06	1.7E-04	7.1E-04	1.4E-06	6.3E-04	4.9E-02	5.7E-07	8.6E-04	6.6E-03	1.6E-04	6.9E-04	1.9E-06	1.0E-03	4.2E-04	2.3E-06
	Adult	3.8E-03	9.5E-06	1.0E-05	1.6E-04	6.8E-04	5.5E-07	7.8E-04	6.4E-02	2.2E-07	1.3E-03	2.7E-03	2.6E-05	9.7E-04	1.1E-06	1.5E-03	3.2E-04	5.2E-06

TABLE 6. TOTAL BDCF IN SV/A PER BQ/L FOR REFERENCE REGION SANTANDER

Source	Person	Am-243	Cl-36	Cs-135	I-129	Nb-94	Ni-59	Np-237	Pa-231	Pd-107	Pu-239	Ra-226	Se-79	Sn-126	Tc-99	Th-230	U-238	Zr-93
Sand Well	Infant	2.1E-04	3.8E-05	3.7E-05	9.9E-05	6.1E-05	5.1E-07	5.3E-05	7.8E-04	2.7E-07	1.5E-04	1.9E-03	2.0E-05	8.6E-05	1.8E-06	4.2E-04	6.1E-05	2.3E-07
	Child	2.4E-04	1.9E-05	4.3E-05	1.2E-04	5.7E-05	2.7E-07	4.2E-05	1.1E-03	1.3E-07	1.7E-04	2.3E-03	1.6E-05	7.2E-05	7.7E-07	4.4E-04	5.2E-05	2.6E-07
	Adult	3.6E-04	7.0E-06	3.6E-05	1.2E-04	5.5E-05	1.5E-07	8.9E-05	1.5E-03	6.5E-08	3.0E-04	9.6E-04	4.1E-06	2.2E-04	6.8E-07	6.2E-04	5.6E-05	1.0E-06
Sand RGW	Infant	2.9E-04	3.2E-05	3.8E-05	7.8E-05	6.4E-05	4.4E-07	5.0E-05	8.1E-04	2.1E-07	1.5E-04	1.3E-02	1.8E-05	8.5E-05	1.3E-06	4.4E-04	6.0E-05	2.2E-07
	Child	3.4E-04	1.6E-05	4.3E-05	9.7E-05	6.1E-05	2.3E-07	4.0E-05	1.2E-03	9.6E-08	1.7E-04	1.7E-02	1.4E-05	7.3E-05	5.4E-07	4.5E-04	5.2E-05	2.5E-07
	Adult	4.9E-04	6.0E-06	3.7E-05	1.0E-04	5.9E-05	1.2E-07	8.5E-05	1.6E-03	5.1E-08	3.0E-04	7.1E-03	3.8E-06	2.1E-04	5.7E-07	6.4E-04	5.5E-05	1.0E-06
Loam Well	Infant	3.3E-04	3.7E-05	2.1E-04	1.0E-04	5.6E-04	5.8E-07	5.5E-05	1.6E-03	3.9E-07	2.0E-04	1.3E-03	4.7E-05	2.0E-04	2.2E-06	5.0E-03	1.1E-04	1.5E-06
	Child	4.0E-04	1.9E-05	2.3E-04	1.3E-04	5.3E-04	2.9E-07	4.5E-05	2.5E-03	1.8E-07	2.6E-04	1.7E-03	3.8E-05	1.8E-04	9.4E-07	5.3E-03	9.5E-05	1.8E-06
	Adult	5.6E-04	8.1E-06	1.7E-04	1.2E-04	5.1E-04	1.5E-07	9.1E-05	3.3E-03	8.5E-08	4.1E-04	7.3E-04	7.3E-06	3.5E-04	7.9E-07	5.5E-03	8.1E-05	3.9E-06
Loam RGW	Infant	9.1E-04	2.8E-05	2.2E-04	8.3E-05	9.2E-04	5.5E-07	5.3E-05	2.0E-03	3.5E-07	2.3E-04	3.8E-03	4.8E-05	2.1E-04	1.6E-06	8.8E-03	1.1E-04	1.6E-06
	Child	1.2E-03	1.5E-05	2.5E-04	1.0E-04	8.8E-04	2.6E-07	4.3E-05	3.3E-03	1.6E-07	2.9E-04	5.4E-03	3.9E-05	2.0E-04	6.5E-07	9.8E-03	1.0E-04	1.9E-06
	Adult	1.6E-03	6.3E-06	1.8E-04	1.1E-04	8.5E-04	1.3E-07	8.8E-05	4.2E-03	7.3E-08	4.7E-04	2.2E-03	7.2E-06	3.5E-04	6.3E-07	1.1E-02	8.3E-05	4.1E-06
Clay Well	Infant	4.0E-04	2.6E-05	2.8E-04	1.1E-04	5.1E-04	2.4E-06	6.1E-05	2.0E-03	5.0E-07	2.8E-04	1.8E-03	4.7E-05	2.6E-04	2.2E-06	1.7E-03	3.3E-05	2.0E-06
	Child	4.6E-04	1.3E-05	3.1E-04	1.3E-04	4.9E-04	1.2E-06	4.8E-05	3.1E-03	2.3E-07	3.5E-04	2.4E-03	3.8E-05	2.4E-04	9.5E-07	1.8E-03	2.8E-05	2.1E-06
	Adult	6.3E-04	5.5E-06	2.1E-04	1.2E-04	4.7E-04	5.2E-07	9.4E-05	4.0E-03	1.0E-07	5.4E-04	9.3E-04	7.3E-06	2.4E-04	7.9E-07	1.7E-03	4.0E-05	4.4E-06
Clay RGW	Infant	1.9E-03	1.6E-05	3.4E-04	9.0E-05	8.8E-04	2.8E-06	6.0E-05	3.0E-03	5.0E-07	3.8E-04	1.2E-01	5.2E-05	3.1E-04	1.5E-06	2.3E-03	3.2E-05	2.3E-06
	Child	2.3E-03	7.8E-06	3.7E-04	1.1E-04	8.4E-04	1.4E-06	4.8E-05	4.7E-03	2.3E-07	4.8E-04	1.8E-01	4.2E-05	2.9E-04	6.2E-07	2.5E-03	2.7E-05	2.4E-06
	Adult	3.0E-03	3.5E-06	2.6E-04	1.1E-04	8.2E-04	6.0E-07	9.3E-05	6.0E-03	9.5E-08	7.2E-04	7.0E-02	7.6E-06	2.8E-04	6.1E-07	2.3E-03	3.9E-05	5.1E-06
Organic Well	Infant	2.8E-04	5.0E-05	2.0E-05	1.3E-04	4.6E-04	2.5E-06	3.5E-04	3.4E-03	1.1E-06	1.8E-04	1.3E-03	1.7E-04	6.0E-04	9.1E-06	3.8E-04	3.1E-04	1.1E-06
	Child	3.4E-04	2.6E-05	2.3E-05	1.6E-04	4.4E-04	1.2E-06	3.1E-04	5.7E-03	5.1E-07	2.3E-04	1.7E-03	1.4E-04	5.7E-04	3.9E-06	4.0E-04	2.8E-04	1.4E-06
	Adult	4.8E-04	1.0E-05	2.1E-05	1.3E-04	4.2E-04	4.6E-07	3.3E-04	7.0E-03	1.9E-07	3.7E-04	6.9E-04	2.1E-05	8.0E-04	2.4E-06	5.7E-04	2.0E-04	3.0E-06
Organic RGW	Infant	5.7E-04	4.5E-05	2.2E-05	1.1E-04	7.4E-04	2.8E-06	3.9E-04	6.5E-03	1.1E-06	2.0E-04	4.4E-03	1.9E-04	7.1E-04	9.5E-06	4.3E-04	3.5E-04	1.2E-06
	Child	7.6E-04	2.3E-05	2.5E-05	1.4E-04	7.1E-04	1.4E-06	3.4E-04	1.1E-02	5.4E-07	2.7E-04	6.0E-03	1.6E-04	6.8E-04	4.0E-06	4.5E-04	3.2E-04	1.5E-06
	Adult	1.0E-03	9.2E-06	2.3E-05	1.2E-04	6.8E-04	5.0E-07	3.6E-04	1.4E-02	1.9E-07	4.2E-04	2.3E-03	2.4E-05	9.2E-04	2.5E-06	6.2E-04	2.2E-04	3.2E-06

TABLE 7. TOTAL BDCF IN SV/A PER BQ/L FOR REFERENCE REGION MAGDEBURG

Source	Person	Am-243	Cl-36	Cs-135	I-129	Nb-94	Ni-59	Np-237	Pa-231	Pd-107	Pu-239	Ra-226	Se-79	Sn-126	Tc-99	Th-230	U-238	Zr-93
Sand Well	Infant	3.2E-04	4.1E-05	4.0E-05	9.4E-05	1.3E-04	5.5E-07	5.4E-05	1.3E-03	2.9E-07	1.9E-04	2.1E-03	2.0E-05	1.6E-04	1.7E-06	5.4E-04	6.6E-05	2.0E-07
	Child	4.3E-04	2.3E-05	4.9E-05	1.2E-04	1.3E-04	3.3E-07	4.6E-05	2.1E-03	1.5E-07	2.6E-04	2.9E-03	1.7E-05	1.5E-04	7.5E-07	6.7E-04	6.5E-05	2.4E-07
	Adult	6.1E-04	9.8E-06	4.6E-05	1.2E-04	1.3E-04	1.9E-07	9.2E-05	2.8E-03	8.0E-08	4.3E-04	1.3E-03	4.4E-06	1.5E-04	6.6E-07	7.7E-04	6.5E-05	9.5E-07
Sand RGW	Infant	2.4E-04	1.6E-05	1.8E-05	6.6E-05	6.1E-05	2.5E-07	4.7E-05	7.3E-04	1.4E-07	1.3E-04	6.8E-03	1.2E-05	7.5E-05	1.1E-06	2.9E-04	4.2E-05	1.9E-07
	Child	3.2E-04	8.9E-06	2.2E-05	8.4E-05	5.9E-05	1.4E-07	3.8E-05	1.1E-03	6.7E-08	1.6E-04	9.9E-03	9.7E-06	6.8E-05	4.8E-07	3.4E-04	3.9E-05	2.1E-07
	Adult	4.7E-04	4.1E-06	2.1E-05	9.4E-05	5.9E-05	9.9E-08	8.4E-05	1.6E-03	4.3E-08	2.9E-04	4.6E-03	3.1E-06	6.7E-05	5.2E-07	4.3E-04	4.8E-05	9.0E-07
Loam Well	Infant	5.5E-04	4.3E-05	2.1E-04	1.0E-04	1.2E-03	6.0E-07	5.8E-05	3.0E-03	4.4E-07	3.0E-04	1.8E-03	5.0E-05	4.2E-04	2.0E-06	6.5E-03	1.3E-04	1.8E-06
	Child	7.7E-04	2.7E-05	2.5E-04	1.3E-04	1.2E-03	3.1E-07	4.9E-05	5.2E-03	2.4E-07	4.4E-04	2.6E-03	4.4E-05	4.0E-04	9.1E-07	8.1E-03	1.3E-04	2.6E-06
	Adult	1.1E-03	1.3E-05	2.0E-04	1.2E-04	1.2E-03	1.6E-07	9.6E-05	6.8E-03	1.1E-07	6.8E-04	1.1E-03	8.9E-06	4.0E-04	7.6E-07	8.0E-03	1.1E-04	5.4E-06
Loam RGW	Infant	7.9E-04	1.6E-05	9.8E-05	6.9E-05	8.7E-04	2.8E-07	4.9E-05	1.8E-03	2.1E-07	2.0E-04	2.5E-03	2.6E-05	2.0E-04	1.2E-06	5.3E-03	7.2E-05	9.2E-07
	Child	1.1E-03	9.6E-06	1.1E-04	8.7E-05	8.6E-04	1.4E-07	4.0E-05	3.1E-03	1.1E-07	2.7E-04	4.2E-03	2.2E-05	1.9E-04	5.0E-07	7.0E-03	7.0E-05	1.3E-06
	Adult	1.5E-03	4.8E-06	9.3E-05	9.6E-05	8.4E-04	8.8E-08	8.6E-05	4.1E-03	5.9E-08	4.4E-04	1.9E-03	5.2E-06	1.9E-04	5.4E-07	7.3E-03	6.7E-05	3.0E-06
Clay Well	Infant	6.5E-04	2.9E-05	2.8E-04	1.0E-04	1.1E-03	2.8E-06	6.3E-05	3.7E-03	5.5E-07	4.2E-04	2.4E-03	5.0E-05	5.6E-04	2.1E-06	2.3E-03	3.3E-05	2.1E-06
	Child	8.9E-04	1.7E-05	3.1E-04	1.4E-04	1.1E-03	1.6E-06	5.4E-05	6.6E-03	3.0E-07	6.5E-04	3.8E-03	4.4E-05	5.5E-04	9.3E-07	2.9E-03	3.0E-05	3.1E-06
	Adult	1.2E-03	8.0E-06	2.3E-04	1.2E-04	1.1E-03	7.6E-07	1.0E-04	8.5E-03	1.4E-07	9.5E-04	1.6E-03	8.8E-06	5.4E-04	7.6E-07	3.0E-03	4.1E-05	6.3E-06
Clay RGW	Infant	1.5E-03	8.9E-06	1.4E-04	7.1E-05	8.4E-04	1.4E-06	5.2E-05	2.6E-03	2.8E-07	3.0E-04	8.0E-02	2.8E-05	2.9E-04	1.2E-06	1.4E-03	2.8E-05	1.2E-06
	Child	2.1E-03	5.0E-06	1.6E-04	9.0E-05	8.2E-04	8.1E-07	4.3E-05	4.5E-03	1.5E-07	4.5E-04	1.5E-01	2.4E-05	2.8E-04	5.1E-07	1.8E-03	2.5E-05	1.7E-06
	Adult	2.8E-03	2.6E-06	1.2E-04	9.7E-05	8.1E-04	4.0E-07	8.9E-05	5.8E-03	7.4E-08	6.8E-04	6.3E-02	5.4E-06	2.8E-04	5.3E-07	1.9E-03	3.7E-05	3.6E-06
Organic Well	Infant	4.5E-04	5.7E-05	2.2E-05	1.2E-04	1.0E-03	2.5E-06	4.5E-04	6.7E-03	1.2E-06	2.7E-04	1.8E-03	1.9E-04	1.3E-03	8.8E-06	4.8E-04	3.5E-04	1.3E-06
	Child	6.2E-04	3.5E-05	2.6E-05	1.6E-04	1.0E-03	1.3E-06	4.3E-04	1.2E-02	6.8E-07	3.9E-04	2.4E-03	1.7E-04	1.3E-03	4.1E-06	5.8E-04	3.6E-04	1.9E-06
	Adult	8.7E-04	1.6E-05	2.6E-05	1.3E-04	9.9E-04	5.2E-07	4.9E-04	1.5E-02	2.8E-07	5.9E-04	1.0E-03	2.9E-05	1.3E-03	2.5E-06	6.7E-04	2.6E-04	4.0E-06
Organic RGW	Infant	4.9E-04	2.4E-05	1.1E-05	8.1E-05	7.0E-04	1.2E-06	2.4E-04	5.9E-03	6.0E-07	1.8E-04	3.0E-03	9.4E-05	6.8E-04	4.5E-06	2.8E-04	1.8E-04	7.1E-07
	Child	6.9E-04	1.4E-05	1.3E-05	1.0E-04	6.9E-04	6.3E-07	2.3E-04	1.1E-02	3.2E-07	2.5E-04	4.3E-03	8.3E-05	6.7E-04	2.1E-06	3.2E-04	1.8E-04	1.0E-06
	Adult	9.6E-04	6.6E-06	1.4E-05	1.0E-04	6.8E-04	2.7E-07	2.8E-04	1.4E-02	1.4E-07	4.0E-04	1.9E-03	1.5E-05	6.6E-04	1.4E-06	4.1E-04	1.4E-04	2.4E-06

TABLE 8. TOTAL BDCF IN SV/A PER BQ/L FOR REFERENCE REGION ROSTOV

Source	Person	Am-243	Cl-36	Cs-135	I-129	Nb-94	Ni-59	Np-237	Pa-231	Pd-107	Pu-239	Ra-226	Se-79	Sn-126	Tc-99	Th-230	U-238	Zr-93
Sand Well	Infant	2.3E-03	4.1E-05	7.9E-05	3.5E-04	2.0E-03	2.0E-06	1.5E-03	4.0E-02	9.8E-07	1.5E-03	3.1E-03	9.9E-05	3.7E-03	8.8E-06	2.4E-03	8.9E-04	1.7E-05
	Child	5.8E-04	7.4E-05	2.0E-03	3.7E-04	2.7E-04	1.3E-06	1.0E-04	7.0E-03	6.4E-07	4.8E-03	1.1E-02	8.4E-05	3.3E-04	2.5E-06	1.5E-03	1.9E-04	1.1E-04
	Adult	6.8E-03	3.4E-05	7.3E-05	4.0E-04	2.0E-03	3.2E-06	2.9E-03	1.5E-01	9.9E-07	4.1E-03	3.6E-03	1.0E-04	3.7E-03	7.1E-06	5.3E-03	1.4E-03	2.0E-05
Sand RGW	Infant	1.3E-03	8.7E-06	2.2E-05	1.6E-04	6.8E-04	5.0E-07	4.4E-04	1.8E-02	2.3E-07	6.0E-04	3.0E-03	2.6E-05	1.0E-03	2.5E-06	8.2E-04	2.5E-04	5.0E-06
	Child	2.5E-04	1.4E-05	4.3E-04	1.3E-04	6.2E-05	2.5E-07	5.8E-05	1.9E-03	1.1E-07	1.2E-03	2.0E-02	2.2E-05	7.7E-05	7.8E-07	4.2E-04	6.5E-05	2.3E-05
	Adult	7.0E-02	7.9E-06	1.1E-04	6.6E-04	1.1E-03	1.0E-05	1.3E-02	6.9E-01	3.5E-06	2.7E-02	5.2E-02	4.8E-04	1.7E-02	2.4E-06	3.2E-02	8.2E-03	5.5E-04
Loam Well	Infant	4.1E-02	1.5E-04	1.7E-03	4.9E-04	4.0E-03	8.0E-06	5.9E-04	1.9E-01	6.3E-06	3.2E-02	2.9E-02	7.5E-04	2.1E-03	6.5E-06	3.4E-01	4.2E-03	3.7E-04
	Child	5.9E-03	6.1E-05	6.0E-04	3.7E-04	2.5E-03	9.8E-07	1.4E-04	4.8E-02	7.7E-07	3.5E-03	7.4E-03	1.2E-04	8.5E-04	3.0E-06	4.7E-02	4.5E-04	1.2E-05
	Adult	8.4E-03	3.3E-05	7.1E-04	3.0E-04	2.5E-03	6.3E-07	2.3E-04	6.2E-02	4.1E-07	5.1E-03	3.5E-03	2.9E-05	1.3E-03	2.2E-06	6.7E-02	4.0E-04	2.8E-05
Loam RGW	Infant	2.9E-03	2.6E-05	1.9E-04	1.1E-04	9.1E-04	5.3E-07	7.9E-05	7.5E-03	3.7E-07	6.6E-04	4.3E-03	4.8E-05	2.2E-04	2.1E-06	1.6E-02	1.5E-04	2.4E-06
	Child	4.5E-03	1.1E-05	1.4E-04	1.3E-04	8.7E-04	1.9E-07	6.5E-05	1.4E-02	1.5E-07	1.0E-03	6.0E-03	3.1E-05	2.0E-04	8.5E-07	2.1E-02	1.2E-04	2.9E-06
	Adult	6.4E-03	6.2E-06	1.6E-04	1.5E-04	8.5E-04	1.5E-07	1.4E-04	1.8E-02	9.5E-08	1.5E-03	2.9E-03	8.6E-06	4.2E-04	8.8E-07	3.0E-02	1.3E-04	7.5E-06
Clay Well	Infant	4.5E-03	5.6E-05	5.3E-04	2.6E-04	2.3E-03	6.4E-06	1.6E-04	3.3E-02	1.5E-06	3.3E-03	5.9E-03	1.1E-04	1.2E-03	5.9E-06	1.1E-02	7.2E-05	1.1E-05
	Child	7.0E-03	3.9E-05	7.7E-04	4.0E-04	2.3E-03	4.4E-06	1.7E-04	6.1E-02	9.6E-07	5.5E-03	1.1E-02	1.2E-04	1.1E-03	3.0E-06	1.8E-02	7.2E-05	1.5E-05
	Adult	9.8E-03	2.1E-05	8.9E-04	3.1E-04	2.3E-03	2.7E-06	2.7E-04	8.0E-02	4.9E-07	7.8E-03	4.8E-03	2.9E-05	1.7E-03	2.2E-06	2.5E-02	8.7E-05	3.4E-05
Clay RGW	Infant	1.2E-04	1.5E-01	2.7E-06	3.0E-03	3.3E-04	1.8E-07	1.3E-03	1.5E-03	1.7E-06	2.1E-02	1.0E-03	7.2E-05	2.8E-05	8.0E-03	1.5E-04	1.3E-03	3.2E-07
	Child	1.1E-04	1.1E-01	3.1E-06	3.9E-03	3.2E-04	9.8E-08	1.6E-03	2.4E-03	1.1E-06	3.6E-02	1.7E-03	7.7E-05	1.4E-05	3.8E-03	1.5E-04	1.5E-03	3.7E-07
	Adult	2.2E-04	5.8E-02	6.2E-06	2.3E-03	3.2E-04	9.8E-08	2.2E-03	3.4E-03	5.6E-07	5.1E-02	9.2E-04	1.9E-05	1.9E-04	2.4E-03	3.9E-04	1.3E-03	1.5E-06
Organic Well	Infant	3.2E-03	2.0E-04	7.9E-05	3.7E-04	2.2E-03	1.0E-05	2.2E-03	6.1E-02	4.8E-06	1.8E-03	6.5E-03	7.3E-04	2.9E-03	3.3E-05	2.7E-03	1.6E-03	6.6E-06
	Child	4.8E-03	7.9E-05	6.5E-05	4.5E-04	2.1E-03	3.4E-06	2.2E-03	1.1E-01	2.0E-06	2.9E-03	7.3E-03	4.5E-04	2.7E-03	1.4E-05	3.4E-03	1.3E-03	8.0E-06
	Adult	6.8E-03	4.1E-05	7.9E-05	3.5E-04	2.0E-03	2.0E-06	2.9E-03	1.5E-01	9.8E-07	4.2E-03	3.3E-03	9.9E-05	3.7E-03	8.8E-06	5.0E-03	1.2E-03	2.0E-05
Organic RGW	Infant	1.8E-03	4.1E-05	2.0E-05	1.3E-04	7.4E-04	2.5E-06	5.8E-04	2.6E-02	1.1E-06	5.6E-04	5.6E-03	1.8E-04	7.3E-04	8.5E-06	7.6E-04	4.0E-04	1.8E-06
	Child	2.7E-03	1.6E-05	1.7E-05	1.5E-04	7.0E-04	8.0E-07	5.5E-04	4.9E-02	4.4E-07	8.5E-04	6.9E-03	1.1E-04	6.8E-04	3.4E-06	9.1E-04	3.3E-04	2.2E-06
	Adult	3.9E-03	8.7E-06	2.2E-05	1.6E-04	6.8E-04	5.0E-07	7.9E-04	6.4E-02	2.3E-07	1.3E-03	3.2E-03	2.6E-05	1.0E-03	2.5E-06	1.5E-03	3.2E-04	5.8E-06

TABLE 9. TOTAL BDCF IN SV/A PER BQ/L FOR REFERENCE REGION TURKU

Source	Person	Am-243	Cl-36	Cs-135	I-129	Nb-94	Ni-59	Np-237	Pa-231	Pd-107	Pu-239	Ra-226	Se-79	Sn-126	Tc-99	Th-230	U-238	Zr-93
Sand Well	Infant	2.0E-04	4.2E-05	4.3E-05	1.4E-04	5.8E-05	5.3E-07	5.2E-05	7.2E-04	2.9E-07	1.4E-04	1.7E-03	2.3E-05	1.3E-04	2.4E-06	4.1E-04	5.6E-05	3.8E-07
	Child	2.4E-04	1.9E-05	4.7E-05	1.7E-04	5.5E-05	2.8E-07	4.3E-05	1.1E-03	1.4E-07	1.7E-04	2.2E-03	1.8E-05	9.0E-05	1.0E-06	4.4E-04	5.1E-05	4.3E-07
	Adult	3.5E-04	7.2E-06	4.3E-05	1.5E-04	5.3E-05	1.6E-07	8.9E-05	1.5E-03	7.0E-08	2.9E-04	8.6E-04	4.8E-06	4.7E-04	8.9E-07	6.2E-04	5.3E-05	1.6E-06
Sand RGW	Infant	2.7E-04	3.6E-05	4.5E-05	1.2E-04	6.5E-05	4.8E-07	5.1E-05	7.8E-04	2.4E-07	1.4E-04	1.1E-02	2.2E-05	1.3E-04	2.0E-06	4.4E-04	5.7E-05	3.7E-07
	Child	3.4E-04	1.7E-05	5.0E-05	1.4E-04	6.1E-05	2.5E-07	4.1E-05	1.2E-03	1.1E-07	1.7E-04	1.5E-02	1.7E-05	9.4E-05	8.1E-07	4.7E-04	5.1E-05	4.2E-07
	Adult	4.9E-04	6.3E-06	4.5E-05	1.3E-04	5.9E-05	1.4E-07	8.6E-05	1.6E-03	5.6E-08	3.0E-04	6.0E-03	4.5E-06	4.6E-04	7.9E-07	6.5E-04	5.3E-05	1.6E-06
Loam Well	Infant	3.2E-04	4.0E-05	2.7E-03	1.5E-04	5.3E-04	6.3E-07	5.5E-05	1.5E-03	4.2E-07	1.9E-04	1.4E-03	5.1E-05	2.3E-04	2.7E-06	4.9E-03	1.0E-04	1.5E-06
	Child	3.9E-04	2.0E-05	2.5E-03	1.8E-04	5.1E-04	3.1E-07	4.5E-05	2.4E-03	2.0E-07	2.5E-04	1.9E-03	4.0E-05	1.9E-04	1.1E-06	5.2E-03	9.2E-05	1.8E-06
	Adult	5.4E-04	7.9E-06	2.6E-03	1.6E-04	4.8E-04	1.6E-07	9.1E-05	3.1E-03	9.0E-08	3.9E-04	7.5E-04	7.9E-06	5.9E-04	9.5E-07	5.4E-03	7.7E-05	4.0E-06
Loam RGW	Infant	9.0E-04	3.2E-05	3.2E-03	1.2E-04	9.2E-04	6.2E-07	5.4E-05	2.0E-03	3.9E-07	2.2E-04	4.1E-03	5.5E-05	2.6E-04	2.2E-06	9.1E-03	1.1E-04	1.6E-06
	Child	1.2E-03	1.6E-05	2.9E-03	1.4E-04	8.8E-04	2.9E-07	4.3E-05	3.2E-03	1.8E-07	2.9E-04	5.8E-03	4.3E-05	2.2E-04	8.8E-07	1.0E-02	1.0E-04	2.0E-06
	Adult	1.6E-03	6.5E-06	3.0E-03	1.4E-04	8.5E-04	1.4E-07	8.9E-05	4.2E-03	8.0E-08	4.6E-04	2.3E-03	8.1E-06	6.1E-04	8.3E-07	1.1E-02	8.1E-05	4.4E-06
Clay Well	Infant	3.7E-04	3.0E-05	5.5E-04	1.5E-04	4.9E-04	2.6E-06	5.9E-05	1.8E-03	5.2E-07	2.5E-04	1.8E-03	5.1E-05	2.9E-04	2.7E-06	1.7E-03	3.3E-05	1.7E-06
	Child	4.5E-04	1.4E-05	5.4E-04	1.8E-04	4.7E-04	1.3E-06	4.8E-05	3.0E-03	2.5E-07	3.4E-04	2.5E-03	4.1E-05	2.5E-04	1.2E-06	1.8E-03	2.8E-05	2.2E-06
	Adult	6.0E-04	5.7E-06	4.6E-04	1.6E-04	4.5E-04	5.7E-07	9.3E-05	3.8E-03	1.1E-07	5.1E-04	9.5E-04	7.9E-06	6.6E-04	9.5E-07	2.0E-03	3.9E-05	4.5E-06
Clay RGW	Infant	1.7E-03	1.9E-05	7.0E-04	1.3E-04	8.8E-04	3.3E-06	6.0E-05	2.8E-03	5.5E-07	3.4E-04	1.2E-01	5.9E-05	3.5E-04	2.1E-06	2.3E-03	3.2E-05	2.0E-06
	Child	2.3E-03	8.8E-06	6.8E-04	1.5E-04	8.5E-04	1.6E-06	4.9E-05	4.7E-03	2.6E-07	4.8E-04	1.9E-01	4.6E-05	3.1E-04	8.7E-07	2.6E-03	2.8E-05	2.6E-06
	Adult	3.0E-03	3.8E-06	5.7E-04	1.4E-04	8.2E-04	6.9E-07	9.3E-05	6.0E-03	1.0E-07	7.1E-04	7.3E-02	8.6E-06	7.2E-04	8.2E-07	2.9E-03	3.9E-05	5.3E-06
Organic Well	Infant	1.6E-04	8.0E-06	7.0E-05	8.7E-05	4.0E-04	4.8E-07	1.9E-04	1.9E-03	1.5E-07	1.1E-04	4.7E-04	1.9E-05	7.6E-04	1.0E-06	2.8E-04	1.1E-04	1.6E-06
	Child	3.2E-04	2.6E-05	8.2E-05	2.1E-04	4.2E-04	1.2E-06	2.9E-04	5.4E-03	5.2E-07	2.2E-04	1.8E-03	1.4E-04	5.6E-04	3.3E-06	3.9E-04	2.6E-04	1.4E-06
	Adult	4.6E-04	9.9E-06	9.1E-05	1.7E-04	4.0E-04	4.7E-07	3.0E-04	6.6E-03	2.0E-07	3.6E-04	7.0E-04	2.2E-05	1.0E-03	2.0E-06	5.6E-04	1.7E-04	3.2E-06
Organic RGW	Infant	3.6E-04	7.4E-06	8.3E-05	7.7E-05	6.8E-04	5.7E-07	2.2E-04	3.9E-03	1.6E-07	1.2E-04	1.7E-03	2.2E-05	9.2E-04	1.1E-06	3.2E-04	1.3E-04	1.9E-06
	Child	7.5E-04	2.5E-05	9.7E-05	1.8E-04	7.1E-04	1.5E-06	3.4E-04	1.1E-02	5.8E-07	2.6E-04	6.2E-03	1.7E-04	7.0E-04	3.5E-06	4.6E-04	3.1E-04	1.6E-06
	Adult	1.0E-03	9.3E-06	1.1E-04	1.5E-04	6.8E-04	5.4E-07	3.4E-04	1.4E-02	2.1E-07	4.1E-04	2.3E-03	2.6E-05	1.2E-03	2.1E-06	6.3E-04	2.0E-04	3.6E-06

TABLE 10. TOTAL BDCF IN SV/A PER BQ/L FOR REFERENCE REGION SODANKYLA

Source	Person	Am-243	Cl-36	Cs-135	I-129	Nb-94	Ni-59	Np-237	Pa-231	Pd-107	Pu-239	Ra-226	Se-79	Sn-126	Tc-99	Th-230	U-238	Zr-93
Sand Well	Infant	1.2E-04	1.7E-05	1.7E-05	1.2E-04	1.9E-05	2.5E-07	4.7E-05	4.1E-04	1.6E-07	1.0E-04	6.9E-04	1.5E-05	8.3E-05	2.1E-06	1.9E-04	3.5E-05	3.7E-07
	Child	1.2E-04	7.6E-06	1.9E-05	1.5E-04	1.8E-05	1.3E-07	3.8E-05	5.3E-04	7.1E-08	1.1E-04	8.7E-04	1.1E-05	4.9E-05	8.8E-07	1.9E-04	3.1E-05	4.2E-07
	Adult	2.1E-04	3.3E-06	2.2E-05	1.4E-04	1.7E-05	9.0E-08	8.4E-05	8.1E-04	4.6E-08	2.2E-04	4.2E-04	3.8E-06	4.1E-04	8.2E-07	3.5E-04	4.1E-05	1.5E-06
Sand RGW	Infant	2.7E-04	3.6E-05	4.5E-05	1.2E-04	6.5E-05	4.8E-07	5.1E-05	7.8E-04	2.4E-07	1.4E-04	1.1E-02	2.2E-05	1.3E-04	2.0E-06	4.4E-04	5.7E-05	3.7E-07
	Child	3.4E-04	1.7E-05	5.0E-05	1.4E-04	6.1E-05	2.5E-07	4.1E-05	1.2E-03	1.1E-07	1.7E-04	1.5E-02	1.7E-05	9.4E-05	8.1E-07	4.7E-04	5.1E-05	4.2E-07
	Adult	4.9E-04	6.3E-06	4.5E-05	1.3E-04	5.9E-05	1.4E-07	8.6E-05	1.6E-03	5.6E-08	3.0E-04	6.0E-03	4.5E-06	4.6E-04	7.9E-07	6.5E-04	5.3E-05	1.6E-06
Loam Well	Infant	1.5E-04	1.7E-05	8.4E-04	1.2E-04	1.6E-04	2.8E-07	4.8E-05	6.4E-04	2.0E-07	1.2E-04	5.9E-04	2.3E-05	1.2E-04	2.2E-06	1.6E-03	4.9E-05	7.0E-07
	Child	1.7E-04	7.8E-06	7.6E-04	1.5E-04	1.5E-04	1.3E-07	3.8E-05	9.3E-04	8.9E-08	1.3E-04	7.7E-04	1.8E-05	8.1E-05	9.1E-07	1.6E-03	4.3E-05	8.5E-07
	Adult	2.7E-04	3.5E-06	8.0E-04	1.4E-04	1.5E-04	9.1E-08	8.4E-05	1.3E-03	5.2E-08	2.5E-04	3.8E-04	4.7E-06	4.5E-04	8.4E-07	1.8E-03	4.8E-05	2.3E-06
Loam RGW	Infant	9.0E-04	3.2E-05	3.2E-03	1.2E-04	9.2E-04	6.2E-07	5.4E-05	2.0E-03	3.9E-07	2.2E-04	4.1E-03	5.5E-05	2.6E-04	2.2E-06	9.1E-03	1.1E-04	1.6E-06
	Child	1.2E-03	1.6E-05	2.9E-03	1.4E-04	8.8E-04	2.9E-07	4.3E-05	3.2E-03	1.8E-07	2.9E-04	5.8E-03	4.3E-05	2.2E-04	8.8E-07	1.0E-02	1.0E-04	2.0E-06
	Adult	1.6E-03	6.5E-06	3.0E-03	1.4E-04	8.5E-04	1.4E-07	8.9E-05	4.2E-03	8.0E-08	4.6E-04	2.3E-03	8.1E-06	6.1E-04	8.3E-07	1.1E-02	8.1E-05	4.4E-06
Clay Well	Infant	1.7E-03	1.9E-05	7.0E-04	1.3E-04	8.8E-04	3.3E-06	6.0E-05	2.8E-03	5.5E-07	3.4E-04	1.2E-01	5.9E-05	3.5E-04	2.1E-06	2.3E-03	3.2E-05	2.0E-06
	Child	1.9E-04	6.0E-06	1.7E-04	1.5E-04	1.4E-04	4.4E-07	3.9E-05	1.1E-03	1.0E-07	1.6E-04	9.8E-04	1.8E-05	9.9E-05	9.2E-07	6.0E-04	2.4E-05	9.5E-07
	Adult	2.9E-04	2.8E-06	1.5E-04	1.4E-04	1.4E-04	2.2E-07	8.5E-05	1.5E-03	5.7E-08	2.8E-04	4.4E-04	4.7E-06	4.7E-04	8.4E-07	7.8E-04	3.7E-05	2.4E-06
Clay RGW	Infant	3.6E-04	2.8E-05	5.5E-04	1.4E-04	4.9E-04	2.6E-06	5.7E-05	1.8E-03	4.8E-07	2.5E-04	1.8E-03	5.0E-05	2.9E-04	2.6E-06	1.7E-03	3.1E-05	1.7E-06
	Child	2.8E-02	8.8E-06	8.3E-04	1.9E-04	9.7E-04	3.1E-06	1.1E-04	4.1E-02	5.8E-07	7.5E-03	6.4E-01	9.5E-05	4.1E-04	8.7E-07	1.8E-02	5.5E-05	6.0E-05
	Adult	3.0E-03	3.8E-06	5.7E-04	1.4E-04	8.2E-04	6.9E-07	9.3E-05	6.0E-03	1.0E-07	7.1E-04	7.3E-02	8.6E-06	7.2E-04	8.2E-07	2.9E-03	3.9E-05	5.3E-06
Organic Well	Infant	1.2E-04	9.7E-06	2.9E-05	1.6E-04	1.3E-04	4.2E-07	1.0E-04	1.0E-03	1.9E-07	1.1E-04	7.4E-04	4.9E-05	1.9E-04	1.6E-06	1.5E-04	9.2E-05	7.1E-07
	Child	1.5E-04	9.7E-06	2.9E-05	1.6E-04	1.3E-04	4.2E-07	1.1E-04	1.8E-03	1.9E-07	1.3E-04	7.4E-04	4.9E-05	1.9E-04	1.6E-06	1.7E-04	9.4E-05	7.2E-07
	Adult	2.5E-04	4.1E-06	3.6E-05	1.4E-04	1.2E-04	1.9E-07	1.5E-04	2.4E-03	8.5E-08	2.4E-04	3.7E-04	9.0E-06	5.8E-04	1.2E-06	3.3E-04	7.7E-05	2.1E-06
Organic RGW	Infant	4.4E-04	2.5E-05	9.7E-05	1.8E-04	7.1E-04	1.5E-06	3.0E-04	5.1E-03	5.8E-07	1.8E-04	6.2E-03	1.7E-04	7.0E-04	3.5E-06	3.8E-04	3.0E-04	1.6E-06
	Child	7.5E-04	2.5E-05	9.7E-05	1.8E-04	7.1E-04	1.5E-06	3.4E-04	1.1E-02	5.8E-07	2.6E-04	6.2E-03	1.7E-04	7.0E-04	3.5E-06	4.6E-04	3.1E-04	1.6E-06
	Adult	1.0E-03	9.3E-06	1.1E-04	1.5E-04	6.8E-04	5.4E-07	3.4E-04	1.4E-02	2.1E-07	4.1E-04	2.3E-03	2.6E-05	1.2E-03	2.1E-06	6.3E-04	2.0E-04	3.6E-06

TABLE 11. TOTAL BDCF IN SV/A PER BQ/L FOR REFERENCE REGION VARDO SINCE IRRIGATION IS 0 L/M^{2}A FOR THE “WELL” SCENARIO, NO BDCF CAN BE DERIVED

Source	**Person**	**Am-243**	**Cl-36**	**Cs-135**	**I-129**	**Nb-94**	**Ni-59**	**Np-237**	**Pa-231**	**Pd-107**	**Pu-239**	**Ra-226**	**Se-79**	**Sn-126**	**Tc-99**	**Th-230**	**U-238**	**Zr-93**
Sand RGW	Infant	2.3E-04	5.4E-06	6.4E-06	8.1E-05	5.9E-05	1.1E-07	4.5E-05	7.0E-04	7.7E-08	1.3E-04	3.6E-03	8.1E-06	7.0E-05	1.1E-06	1.7E-04	2.8E-05	1.7E-07
	Child	3.1E-04	2.6E-06	1.6E-05	1.4E-04	5.8E-05	7.0E-08	3.7E-05	1.1E-03	3.8E-08	1.6E-04	7.1E-03	9.3E-06	8.9E-05	7.6E-07	2.1E-04	2.5E-05	3.9E-07
	Adult	4.7E-04	1.8E-06	2.8E-05	1.4E-04	5.8E-05	7.6E-08	8.4E-05	1.6E-03	3.7E-08	2.9E-04	4.6E-03	3.6E-06	4.2E-04	7.5E-07	4.1E-04	3.9E-05	1.5E-06
Loam RGW	Infant	2.4E-04	5.3E-06	4.5E-04	9.8E-05	5.9E-05	1.4E-07	4.6E-05	7.0E-04	8.5E-08	1.3E-04	4.6E-03	1.1E-05	1.2E-04	1.8E-06	1.7E-04	2.8E-05	3.4E-07
	Child	3.1E-04	2.6E-06	9.8E-04	1.5E-04	5.8E-05	9.7E-08	3.7E-05	1.1E-03	3.8E-08	1.6E-04	1.1E-02	9.3E-06	8.9E-05	7.6E-07	2.1E-04	2.5E-05	3.9E-07
	Adult	4.7E-04	1.7E-06	1.4E-03	1.4E-04	5.8E-05	9.2E-08	8.4E-05	1.5E-03	3.4E-08	2.9E-04	5.5E-03	3.6E-06	4.2E-04	7.5E-07	4.1E-04	3.8E-05	1.5E-06
Clay RGW	Infant	1.3E-03	5.6E-06	4.1E-04	1.1E-04	8.0E-04	8.4E-07	4.9E-05	2.4E-03	1.1E-07	2.8E-04	2.9E-02	1.5E-05	3.3E-04	1.9E-06	6.1E-04	2.6E-05	6.3E-07
	Child	2.0E-03	2.4E-06	7.8E-04	1.5E-04	8.0E-04	7.2E-07	4.0E-05	4.3E-03	4.8E-08	4.2E-04	4.7E-02	1.4E-05	3.0E-04	7.7E-07	9.0E-04	2.2E-05	8.0E-07
	Adult	2.7E-03	1.6E-06	1.1E-03	1.5E-04	8.0E-04	5.3E-07	8.8E-05	5.6E-03	3.9E-08	6.5E-04	2.8E-02	4.8E-06	6.4E-04	7.6E-07	1.4E-03	3.6E-05	2.2E-06
Organic RGW	Infant	4.7E-04	6.3E-06	8.2E-05	1.1E-04	6.7E-04	3.0E-07	1.2E-04	5.5E-03	1.6E-07	1.7E-04	1.6E-03	3.0E-05	7.1E-04	2.8E-06	1.7E-04	5.6E-05	5.0E-07
	Child	2.2E-03	2.8E-06	1.6E-04	1.8E-04	6.9E-04	5.6E-07	3.8E-04	2.7E-02	2.4E-07	7.8E-04	6.1E-03	7.3E-05	7.2E-04	1.6E-06	6.9E-04	2.9E-04	6.5E-06
	Adult	9.3E-04	1.8E-06	2.3E-04	1.5E-04	6.7E-04	1.8E-07	2.1E-04	1.3E-02	4.8E-08	3.8E-04	1.7E-03	9.8E-06	1.0E-03	1.2E-06	4.2E-04	6.4E-05	1.9E-06

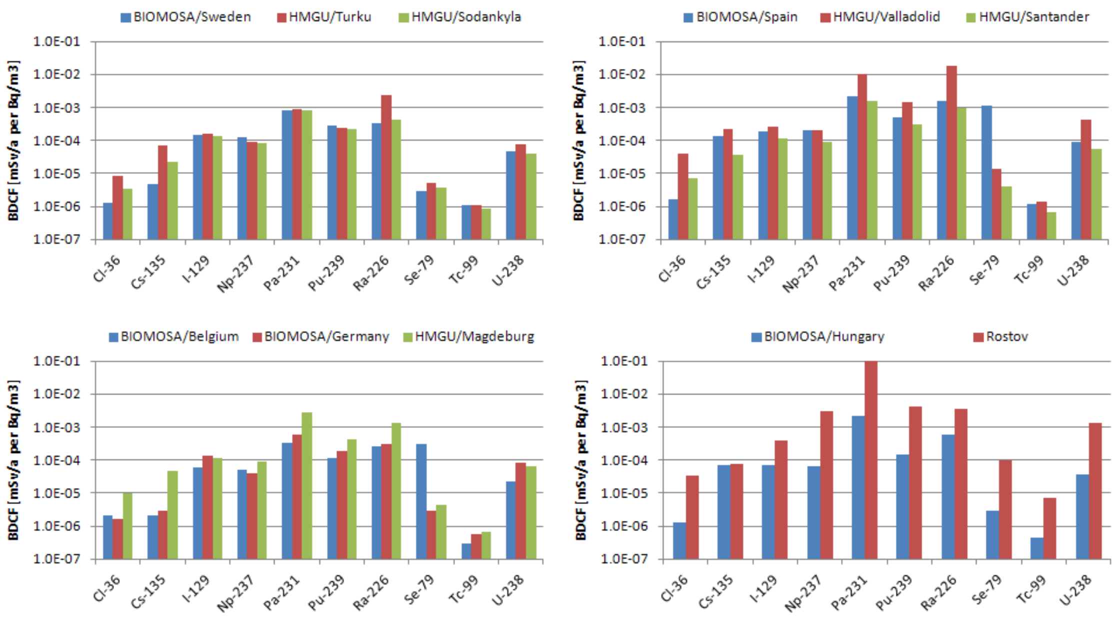


FIG. 10. Comparison of HMGU and BIOMOSA model results.

I.5.2. Comparison of the BDCF with results from other work groups

I.5.2.1. BIOMOSA

The BIOMOSA project compared 5 model approaches developed with the IAEA BIOMASS methodology. The results of this project can be compared with the results from the different HMGU reference climate regions (Figure 10). The results of the different model approaches are comparable for most radionuclides, with some exceptions, mostly for Cl-36, Cs-137 and Se-79.

I.5.2.2. SKB

When the contamination in groundwater used for irrigation and drinking water are unknown or not calculated in the same model, the BDCF may be used as a biosphere modelling endpoint. This may be the case, when the geosphere and biosphere modelling is done by different work groups. To compare BDCF results with results from models integrating the geosphere and biosphere, radionuclide concentrations in groundwater calculated by those models can be used. The annual doses resulting from the multiplication of the groundwater radionuclide concentration with the BDCF can then be compared with the annual doses from the integrated models.

Such a comparison is shown in Table 13 for the HMGU model results and the results of the SKB assessment of the Forsmark site [18]. The annual doses resulting from the multiplication of the groundwater radionuclide concentration in SKB object 136 with the HMGU BDCF are compared with the annual doses from the SKB object 136.

Twelve of the 17 doses of the compared radionuclides are within a 10 fold variation, 7 others within a 20 fold variation. Only the results for Se-79 are very different for both modelling approaches.

TABLE 12. COMPARISON OF SKB [18] AND HMGU MODEL RESULTS

Radionuclide	SKB Well water object 136 [Bq/l]	HMGU BDCF (Sodankyla, sand, adult) [Sv/a per Bq/l]	HMGU BDCF x well water object 136	SKB dose object 136 [Sv]	HMGU dose/SKB dose
Am-243	1.9E-11	2.1E-04	4.0E-15	1.3E-15	3.073
Cl-36	3.8E-08	3.3E-06	1.3E-13	3.1E-13	0.407
Cs-135	4.4E-06	2.2E-05	9.5E-11	1.0E-11	9.188
I-129	4.5E-07	1.4E-04	6.3E-11	1.3E-09	0.049
Nb-94	5.2E-06	1.7E-05	8.8E-11	6.7E-10	0.131
Ni-59	6.5E-04	9.0E-08	5.8E-11	9.0E-10	0.065
Np-237	4.8E-06	8.4E-05	4.1E-10	4.5E-09	0.090
Pa-231	4.2E-07	8.1E-04	3.4E-10	1.1E-10	2.928
Pd-107	6.2E-07	4.6E-08	2.9E-14	4.9E-14	0.583
Pu-239	1.4E-06	2.2E-04	3.1E-10	1.2E-10	2.572
Ra-226	3.6E-04	4.2E-04	1.5E-07	4.5E-08	3.398
Se-79	1.3E-07	3.8E-06	5.1E-13	1.1E-09	0.0005
Sn-126	3.5E-08	4.1E-04	1.5E-11	4.0E-11	0.360
Tc-99	5.0E-06	8.2E-07	4.1E-12	6.1E-11	0.067
Th-230	3.2E-09	3.5E-04	1.1E-12	2.3E-13	4.792
U-238	5.6E-09	4.1E-05	2.3E-13	4.2E-13	0.544
Zr-93	6.3E-05	1.5E-06	9.8E-11	6.8E-11	1.438

TABLE 13. COMPARISON OF NWMO [35] AND HMGU MODEL RESULTS

Radion-uclide	BDCF [mSv/a per Bq/m^3]		Well water [Bq/m^3]	Dose [mSv/a]			HMGU Rostow dose/ NWMO dose	HMGU Toronto dose/ NWMO dose
	HMGU/ Rostov	HMGU/ Toronto	NWMO/ Bruce	HMGU/ Rostow	HMGU/ Toronto	NWMO/ Bruce		
Cl-36	3.4E-05	2.3E-05	1.5E-05	5.2E-10	3.4E-10	3.0E-11	17.2	11.3
I-129	4.0E-04	1.9E-04	3.0E-06	1.2E-09	5.7E-10	4.0E-10	3.0	1.4
Pu-239	4.1E-03	6.6E-04	1.0E-08	4.1E-11	6.6E-12	2.5E-12	16.4	2.7
Th-230	5.3E-03	1.9E-03	5.0E-08	2.6E-10	9.3E-11	3.0E-11	8.8	3.1

I.5.2.3. NWMO

Another comparison may be done by comparing NWMO results for the Bruce site [35] with HMGU model results. By comparing the NWMO results for Bruce with the results from the HMGU Rostov reference region, a good agreement of the resulting doses can be found. This agreement can be improved, if Canadian consumption habits [32] and climate data for Toronto [30] are included into the HMGU model.

I.6. CONCLUSIONS

In this exercise, the setup of a model to calculate Biosphere Dose Conversion Factors (BDCFs) for the exposure to different radionuclides of a self-sustaining population at the location of a high level radioactive waste deep geological repository is presented. The model's FEP list, interaction matrix and mathematical foundation of the model have been presented, following the BIOMASS methodology [1].

Furthermore, the model has been applied to different reference stations to examine the effects of different climates on BDCFs, taking into account how climatic factors influence radionuclide distribution in the biosphere and the relevant exposure pathways. This shows how other sites can been used as analogues for future different climates at a particular site of interest. The approach does not directly address the effect of climate change on the biosphere system itself, nor the interface with the geosphere.

The BDCF results are presented in substantial detail for a relevant set of radionuclides, soil types, age groups and other factors. They demonstrate a pronounced influence of the amount of irrigation needed for agriculture on the peak doses. However, the resulting BDCFs have been demonstrated to be reasonably comparable with the results from other relevant assessment approaches, illustrating the robustness of the model and the modelling approach.

TABLE 14. RESULTS OF SCREENING THE BIOMASS FEP LIST [1]

FEP Identifier	FEP Name	Included (Y/N)?	Comments
1	Assessment context	Y	
1.1	Assessment purpose	Y	Guide to site selection and approval at later stages in repository development
1.2	Assessment endpoints	Y	
1.2.1	Annual individual dose	Y	Calculation of BDCF
1.2.2	Lifetime individual dose	N	
1.2.3	Annual individual risk	N	
1.2.4	Lifetime individual risk	N	
1.2.5	Collective dose/risk	N	
1.2.6	Dose to non-human biota	N	
1.2.7	Modification of the radiation environment	N	
1.2.8	Fluxes	Y	Movements of radionuclides through food chain
1.2.9	Non-radiological endpoints	N	
1.2.10	Uncertainties and/or confidence	Y	Sensitivity analysis of parameters
1.3	Assessment philosophy	Y	User friendly but complete guideline
1.4	Repository system	Y	Final repository in salt dome or clay
1.5	Site context	Y	Agricultural land, pasture and surface water bodies
1.6	Source term	Y	Groundwater 1 Bq/l
1.6.1	Geosphere/biosphere interface	Y	Well, rising groundwater
1.6.2	Release mechanism	Y	Well, rising groundwater
1.6.3	Source term characteristics	Y	Groundwater 1 Bq/l
1.7	Time frames	Y	10^6 years
1.8	Societal assumptions	Y	Societal changes due to climate change
2	Biosphere system features	Y	Current biosphere system in Germany modified by climate change
2.1	Climate	Y	
2.1.1	Description of climate change	Y	Change of irrigation requirements
2.1.2	Identification and characterization of climate categories	Y	For selection of reference stations
2.2	Human society	Y	Agriculture and water use
2.3	Systems of exchange	Y	Agricultural land, pasture and surface water bodies
2.3.1	Environment types	Y	Soil types sand, loam and clay
2.3.1.1	Natural and semi-natural environments	N	
2.3.1.2	Agricultural environments	Y	Agricultural land, pasture and surface water bodies
2.3.1.3	Urban and industrial environments	N	
2.3.2	Ecosystems	Y	
2.3.2.1	Living components of ecosystems	Y	Humans, animals and plant
2.3.2.2	Non-living components of ecosystems	Y	Soil, surface water bodies

TABLE 14. CONTINUED

FEP Identifier	FEP Name	Included (Y/N)?	Comments
3	Biosphere events and processes	Y	
3.1	Natural events and processes	Y	Temperature and humidity
3.1.1	Environmental change	Y	Change in temperature and humidity
3.1.1.1	Physical changes	Y	Activity concentration of radionuclides in soil
3.1.1.2	Chemical changes	N	
3.1.1.3	Ecological changes	Y	Climate change
3.1.2	Environmental dynamics	N	
3.1.2.1	Diurnal variability	N	
3.1.2.2	Seasonal variability	N	
3.1.2.3	Inter-annual and longer timescale variability	Y	Climate change
3.1.3	Cycling and distribution of materials in living components	Y	
3.1.3.1	Transport mediated by flora and fauna	Y	Food chain
3.1.3.1.1	Root uptake	Y	
3.1.3.1.2	Respiration	Y	C-14 model
3.1.3.1.3	Transpiration	N	
3.1.3.1.4	Intake by fauna	Y	Root and leave uptake
3.1.3.1.5	Interception	Y	
3.1.3.1.6	Weathering	Y	
3.1.3.1.7	Bioturbation	N	
3.1.3.2	Metabolism by flora and fauna	Y	
3.1.3.2.1	Translocation	Y	
3.1.3.2.2	Animal metabolism	Y	
3.1.4	Cycling and distribution of materials in non-living components	Y	
3.1.4.1	Atmospheric transport	Y	
3.1.4.1.1	Evaporation	N	
3.1.4.1.2	Gas transport	Y	C-14 model
3.1.4.1.3	Aerosol formation and transport	N	
3.1.4.1.4	Precipitation	N	
3.1.4.1.5	Washout and wet deposition	N	
3.1.4.1.6	Dry deposition	N	
3.1.4.2	Water-borne transport	Y	Groundwater
3.1.4.2.1	Infiltration	Y	
3.1.4.2.2	Percolation	N	
3.1.4.2.3	Capillary rise	N	
3.1.4.2.4	Groundwater transport	Y	Primary source of activity concentration
3.1.4.2.5	Multiphase flow	N	
3.1.4.2.6	Surface run-off	N	
3.1.4.2.7	Discharge	Y	By well
3.1.4.2.8	Recharge	N	
3.1.4.2.9	Transport in surface water bodies	Y	Included in fish model
3.1.4.2.10	Erosion	N	
3.1.4.3	Solid-phase transport	Y	
3.1.4.3.1	Landslides and rock falls	N	
3.1.4.3.2	Sedimentation	Y	Included in fish model
3.1.4.3.3	Sediment suspension	Y	Included in fish model
3.1.4.3.4	Rain splash	N	
3.1.4.4	Physicochemical Changes	Y	
3.1.4.4.1	Dissolution/precipitation	Y	Radionuclide migration in soil
3.1.4.4.2	Adsorption/desorption	Y	Radionuclide migration in soil
3.1.4.4.3	Colloid formation	N	

TABLE 14. CONTINUED

FEP Identifier	FEP Name	Included (Y/N)?	Comments
3.2	Events and processes related to human activity concentration	Y	
3.2.1	Chemical changes	N	
3.2.1.1	Artificial soil fertilization	N	
3.2.1.2	Chemical pollution	N	
3.2.1.3	Acid rain	N	
3.2.2	Physical changes	Y	
3.2.2.1	Construction	N	
3.2.2.2	Water extraction by pumping	Y	Well scenario
3.2.2.3	Water recharge by pumping	N	
3.2.2.4	Dam building	N	
3.2.2.5	Land reclamation	N	
3.2.3	Recycling and mixing of bulk materials	Y	
3.2.3.1	Ploughing	Y	Assumed in arable land soil
3.2.3.2	Well supply	Y	Source of irrigation water
3.2.3.3	Other water supply	Y	Rising groundwater scenario
3.2.3.4	Irrigation	Y	
3.2.3.5	Recycling of bulk solid materials	N	
3.2.3.6	Artificial mixing of water bodies	N	
3.2.3.7	Dredging	N	
3.2.3.8	Controlled ventilation	N	
3.2.4	Redistribution of trace materials	Y	
3.2.4.1	Water treatment	Y	Parameter set to 1 in current model
3.2.4.2	Air filtration	N	
3.2.4.3	Food processing	N	
4	Human exposure features, events and processes	Y	
4.1	Human habits	Y	
4.1.1	Resource usage	Y	Drinking water, plants and animal products
4.1.1.1	Arable food resources	Y	Agricultural plants
4.1.1.2	Animal-derived food resources	Y	Meat and Milk
4.1.1.3	Fodder products	Y	Grass, maize, cereals and water
4.1.1.4	Natural food resources	Y	Berries, fungi, fish and reindeer
4.1.1.5	Non-food uses of biosphere products	N	
4.1.1.6	Water	Y	Drinking water
4.1.2	Storage of products	N	
4.1.3	Location	Y	Different reference stations
4.1.4	Diet	Y	
4.2	External irradiation	Y	
4.2.1	External irradiation from the atmosphere	Y	
4.2.2	External irradiation from soils	Y	
4.2.3	External irradiation from water	N	
4.2.4	External irradiation from sediments	N	
4.2.5	External irradiation from non-food products	N	
4.2.6	External irradiation from the flora and fauna	N	
4.3	Internal exposure	Y	
4.3.1	Inhalation	Y	
4.3.2	Ingestion	Y	
4.3.2.1	Drinking	Y	
4.3.2.2	Food	Y	
4.3.2.3	Soil and sediments	N	
4.3.3	Dermal absorption	N	

TABLE 15. FOOD CONSUMPTION OF DOMESTICATED ANIMALS [kg/d] [24, 36]

Food type	**Marrakesh**	**Rome**	**Valladolid**	**Santander**	**Deutschland**	**Rostov**	**Turku**	**Sodankylä**	**Vardo**
Dairy Cow [kg/d]									
Grass	70	70	70	70	70	70	70	70	70
Maize	0	0	0	0	0	0	0	0	0
Cereals	0	0	0	0	0	0	0	0	0
Water	75	75	75	75	75	75	75	75	75
Beef [kg/d]									
Grass	25	25	25	0	0	25	50	50	
Maize	10	10	10	25	25	10	0	0	
Cereals	0	0	0	0	0	0	1	1	
Water	40	40	60	60	40	40	40	40	
Pork [kg/d]									
Grass	0	0	0	0	0	0	0	0	
Maize	0	0	0	0	0	0	0	0	
Cereals	4	4	4	4	4	4	4	4	
Water	8	8	8	8	8	8	8	8	
Mutton [kg/d]									
Grass	5	5	5	5	5	5	5	5	
Maize	0	0	0	0	0	0	0	0	
Cereals	0	0	0	0	0	0	0	0	
Water	4	4	4	4	4	4	4	4	
Poultry [kg/d]									
Grass	0	0	0	0	0	0	0	0	
Maize	0	0	0	0	0	0	0	0	
Cereals	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	
Water	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	
Reindeer [kg/d]									
Grass									70
Maize									0
Cereals									0
Water									40

TABLE 16. DISTRIBUTION COEFFICIENTS [l/kg] SOIL-WATER [23]

Element	**Sand**	**Loam**	**Clay**	**Organic**
Am	1000.0	4200.0	8100.0	2500.0
Cl	0.5	0.4	0.2	0.7
Cs	530.0	3500.0	5500.0	270.0
I	4.1	8.0	11.0	32.0
Nb	170.0	2500.0	2400.0	2000.0
Ni	130.0	180.0	930.0	1100.0
Np	14.0	23.0	38.0	810.0
Pa	540.0	1800.0	2700.0	6600.0
Pd	90.0	180.0	270.0	670.0
Pu	400.0	950.0	1800.0	760.0
Ra	3100.0	1100.0	38000.0	1300.0
Se	56.0	220.0	240.0	1000.0
Sn	150.0	450.0	670.0	1600.0
Tc	0.0	0.1	0.1	3.1
Th	700.0	18000.0	4500.0	730.0
U	110.0	310.0	28.0	1200.0
Zr	32.0	5200.0	6800.0	3700.0

TABLE 17. TRANSFER FACTORS SOIL TO PLANT SUBTROPICAL CLIMATE [9, 23]

Element	Soil	Cereal	Fruit vegetable	Grass	Leafy vegetable	Maize	Potato	Fruit
Cs	All	3.1E-03	1.9E-02	2.5E-01	3.8E-02		6.5E-02	2.0E-02
	Sand				1.0E-02		1.5E-01	
	Loam	2.5E-03	2.5E-02	2.7E-01	4.1E-02		4.2E-02	2.1E-01
	Clay		7.3E-03		8.0E-03	5.0E-03	4.7E-02	1.7E-02
I		1.5E-04	1.2E-03				5.6E-02	
	Sand				3.5E-02			
Pu			8.2E-04		1.1E-03		1.5E-03	
Tc		3.0E-02	3.0E-01		7.2E-01		5.0E-01	

TABLE 18. TRANSFER FACTORS SAND TO PLANT TEMPERATE CLIMATE [9, 23, 37]

Element	Cereal	Fruit vegetable	Grass	Leafy vegetable	Maize	Potato	Fruit
Am	2.7E-05	3.9E-04	3.3E-02	5.3E-05	2.6E-04	2.1E-04	2.5E-04
Cl	2.5E+01	2.0E+00	2.0E+00	1.6E+01	2.0E+00	2.0E+00	7.0E+01
Cs	3.9E-02	3.5E-02	8.4E-02	1.2E-02	4.9E-02	9.3E-02	2.2E-01
I	5.8E-03	1.0E-01	1.8E-03	4.0E-02	1.0E-01	1.0E-01	4.0E-02
Nb	1.4E-02	8.0E-03	2.0E-02	1.7E-02	4.0E-03	4.0E-03	2.5E-02
Ni	3.7E-02	5.0E-03	2.6E-02	5.0E-03	5.0E-02	5.0E-03	6.0E-02
Np	3.5E-03	1.8E-02	3.1E-02	2.7E-02	4.8E-03	5.8E-03	1.0E-02
Pa	2.0E-04	1.0E-04	5.0E-04	3.0E-04	2.0E-04	1.0E-04	2.5E-04
Pd	3.0E-02	5.0E-03	3.0E-02	2.0E-02	3.0E-02	5.0E-03	4.0E-02
Pu	1.0E-05	6.5E-05	1.6E-04	1.1E-04	3.0E-06	1.0E-04	4.5E-05
Ra	1.7E-02	2.2E-03	1.4E-01	9.1E-01	2.4E-03	1.1E-02	1.2E-02
Se	2.0E-02	3.0E-03	5.0E-02	3.0E-03	2.0E-02	3.0E-03	5.0E-02
Sn	5.0E-03	1.0E-03	5.0E-03	3.0E-03	5.0E-03	1.0E-03	6.0E-03
Tc	1.3E+00	3.0E-01	7.6E+01	1.1E+02	3.8E+00	3.9E-01	1.5E+00
Th	4.4E-03	7.8E-04	4.2E-02	1.2E-03	6.4E-05	2.0E-04	6.3E-03
U	8.9E-03	1.9E-02	1.6E-02	1.7E-01	1.5E-02	1.9E-02	1.2E-02
Zr	1.0E-03	4.0E-03	1.0E-02	4.0E-03	5.0E-04	4.0E-03	1.0E-03

TABLE 19. TRANSFER FACTORS LOAM TO PLANT TEMPERATE CLIMATE [9, 23, 37]

Element	Cereal	Fruit vegetable	Grass	Leafy vegetable	Maize	Potato	Fruit
Am	4.0E-04	3.6E-04	3.3E-02	1.6E-04	2.6E-04	1.5E-04	2.5E-04
Cl	4.7E+01	2.0E+00	2.0E+00	2.5E+01	2.0E+00	2.0E+00	7.0E+01
Cs	2.0E-02	3.3E-02	4.8E-02	7.4E-02	1.6E-02	3.5E-02	2.2E-01
I	3.6E-04	1.0E-01	3.7E-03	4.1E-03	1.0E-01	1.0E-01	4.0E-02
Nb	1.4E-02	8.0E-03	2.0E-02	1.7E-02	4.0E-03	4.0E-03	2.5E-02
Ni	7.6E-03	5.0E-03	1.1E-01	5.0E-03	5.0E-02	5.0E-03	6.0E-02
Np	8.5E-04	1.8E-02	3.1E-02	2.7E-02	4.8E-03	5.7E-03	1.0E-02
Pa	2.0E-04	1.0E-04	5.0E-04	3.0E-04	2.0E-04	1.0E-04	2.5E-04
Pd	3.0E-02	5.0E-03	3.0E-02	2.0E-02	3.0E-02	5.0E-03	4.0E-02
Pu	4.9E-06	6.5E-05	1.6E-04	2.8E-04	3.0E-06	1.5E-04	4.5E-05
Ra	2.9E-02	4.8E-02	2.6E-01	1.2E-01	1.7E-03	1.2E-02	1.2E-02
Se	2.0E-02	3.0E-03	5.0E-02	3.0E-03	2.0E-02	3.0E-03	5.0E-02
Sn	5.0E-03	1.0E-03	5.0E-03	3.0E-03	5.0E-03	1.0E-03	6.0E-03
Tc	1.3E+00	3.0E-01	7.6E+01	2.5E+02	3.8E+00	9.4E-02	1.5E+00
Th	4.4E-03	2.0E-04	4.2E-02	8.6E-04	2.0E-04	2.5E-04	6.3E-03
U	7.7E-03	2.3E-02	9.8E-03	4.3E-02	1.5E-02	2.8E-02	1.2E-02
Zr	1.0E-03	4.0E-03	1.0E-02	4.0E-03	5.0E-04	4.0E-03	1.0E-03

TABLE 20. TRANSFER FACTORS CLAY TO PLANT TEMPERATE CLIMATE [9, 23, 37]

Element	Cereal	Fruit vegetable	Grass	Leafy vegetable	Maize	Potato	Fruit
Am	1.6E-05	3.6E-04	3.3E-02	2.7E-04	2.6E-04	3.3E-03	2.5E-04
Cl	3.7E+01	2.0E+00	2.0E+00	4.5E+01	2.0E+00	2.0E+00	7.0E+01
Cs	1.1E-02	9.1E-03	1.2E-02	1.8E-02	1.2E-02	2.5E-02	2.2E-01
I	5.7E-04	1.0E-01	8.7E-03	4.6E-03	1.0E-01	1.0E-01	4.0E-02
Nb	1.4E-02	8.0E-03	2.0E-02	1.7E-02	4.0E-03	4.0E-03	2.5E-02
Ni	3.2E-02	5.0E-03	2.5E-01	5.0E-03	5.0E-02	5.0E-03	6.0E-02
Np	3.9E-05	1.8E-02	3.1E-02	2.7E-02	4.8E-03	5.7E-03	1.0E-02
Pa	2.0E-04	1.0E-04	5.0E-04	3.0E-04	2.0E-04	1.0E-04	2.5E-04
Pd	3.0E-02	5.0E-03	3.0E-02	2.0E-02	3.0E-02	5.0E-03	4.0E-02
Pu	7.4E-06	6.5E-05	1.6E-04	8.3E-05	3.0E-06	3.6E-04	4.5E-05
Ra	3.9E-02	2.2E-02	4.2E-02	4.0E-02	1.4E-03	5.4E-03	1.2E-02
Se	2.0E-02	3.0E-03	5.0E-02	3.0E-03	2.0E-02	3.0E-03	5.0E-02
Sn	5.0E-03	1.0E-03	5.0E-03	3.0E-03	5.0E-03	1.0E-03	6.0E-03
Tc	1.3E+00	3.0E-01	7.6E+01	1.8E+02	3.8E+00	2.3E-01	1.5E+00
Th	4.4E-03	1.5E-05	4.2E-02	4.9E-04	1.5E-05	9.6E-05	6.3E-03
U	3.8E-03	1.8E-02	1.7E-02	3.6E-03	1.5E-02	9.2E-04	1.2E-02
Zr	1.0E-03	4.0E-03	1.0E-02	4.0E-03	5.0E-04	4.0E-03	1.0E-03

TABLE 21. TRANSFER FACTORS CLAY TO PLANT TEMPERATE CLIMATE [9, 23, 37]

Element	Cereal	Fruit vegetable	Grass	Leafy vegetable	Maize	Potato	Fruit
Am	1.5E-07	3.6E-04	3.3E-02	1.4E-04	2.6E-04	6.7E-04	2.5E-04
Cl	3.6E+01	2.0E+00	2.0E+00	2.6E+01	2.0E+00	1.2E+01	7.0E+01
Cs	4.3E-02	2.3E-02	2.8E-01	2.3E-02	1.4E-01	5.9E-02	2.2E-01
I	6.3E-04	1.0E-01	3.7E-03	6.5E-03	1.0E-01	7.7E-03	4.0E-02
Nb	1.4E-02	8.0E-03	2.0E-02	1.7E-02	4.0E-03	1.7E-02	2.5E-02
Ni	6.1E-03	5.0E-03	2.4E-02	5.0E-03	5.0E-02	5.0E-03	6.0E-02
Np	9.7E-05	1.8E-02	3.1E-02	2.7E-02	4.8E-03	2.2E-02	1.0E-02
Pa	2.0E-04	1.0E-04	5.0E-04	3.0E-04	2.0E-04	1.0E-04	2.5E-04
Pd	3.0E-02	5.0E-03	3.0E-02	2.0E-02	3.0E-02	5.0E-03	4.0E-02
Pu	5.4E-04	6.5E-05	1.6E-04	2.7E-05	3.0E-06	3.9E-04	4.5E-05
Ra	1.7E-02	1.7E-02	1.3E-01	4.9E-02	2.4E-03	7.0E-02	1.2E-02
Se	2.0E-02	3.0E-03	5.0E-02	3.0E-03	2.0E-02	3.0E-03	5.0E-02
Sn	5.0E-03	1.0E-03	5.0E-03	3.0E-03	5.0E-03	1.0E-03	6.0E-03
Tc	1.3E+00	3.0E-01	7.6E+01	1.8E+02	1.7E+01	2.3E-01	1.5E+00
Th	2.1E-03	7.8E-04	4.2E-02	1.2E-03	6.4E-05	8.0E-04	6.3E-03
U	6.2E-03	1.5E-02	1.7E-02	1.8E-01	1.5E-02	5.0E-03	1.2E-02
Zr	1.0E-03	4.0E-03	1.0E-02	4.0E-03	5.0E-04	4.0E-03	1.0E-03

TABLE 22. CAESIUM CAESIUM TRANSFER FACTORS SAND TO PLANT TEMPERATE CLIMATE [38–40]

Element	Cereal	Fruit vegetable	Grass	Leafy vegetable	Maize	Potato	Fruit
Sand	3.1E-02			5.2E-01		8.1E-02	
Loam	3.3E-01		1.1E+01	6.5E-02		3.9E-02	
Clay	1.4E-02		8.2E-01	6.5E-02		3.9E-02	
Organic	3.2E-01		3.3E+00	4.1E-01		8.2E-02	

TABLE 23. TRANSLOCATION FACTORS [28]

Element	Cereal	Fruit vegetable	Grass	Leafy vegetable	Maize	Potato	Fruit
Am	0.005	0.0033	1	1	1	0	0.0033
Cl	0.09	0.1	1	1	1	0.1	0.1
Cs	0.09	0.1	1	1	1	0.1	0.1
I	0.09	0.1	1	1	1	0.1	0.1
Nb	0.005	0.0033	1	1	1	0	0.0033
Ni	0.09	0.1	1	1	1	0.1	0.1
Np	0.005	0.0033	1	1	1	0	0.0033
Pa	0.005	0.0033	1	1	1	0	0.0033
Pd	0.09	0.1	1	1	1	0.1	0.1
Pu	0.005	0.0033	1	1	1	0	0.0033
Ra	0.005	0.0033	1	1	1	0	0.0033
Se	0.09	0.1	1	1	1	0.1	0.1
Sn	0.09	0.1	1	1	1	0.1	0.1
Tc	0.09	0.1	1	1	1	0.1	0.1
Th	0.005	0.0033	1	1	1	0	0.0033
U	0.005	0.0033	1	1	1	0	0.0033
Zr	0.005	0.0033	1	1	1	0	0.0033

TABLE 24. GROWTH PERIODS FOR AGRICULTURAL PLANTS [26]

Site	Grass	Maize	Cereal	Potato	Leafy vegetables	Fruit vegetables	Fruit
Marrakesh	Oct–May	Feb–Jun	Feb–Jun	Jan–May	Feb–Jun	Jan–Jun	Jan–Jun
Rome	Mar–Oct	May–Sep	Apr–Aug	May–Sep	Jan–Dec	Apr–Oct	Apr–Oct
Rostov	May–Sep	May–Aug	May–Aug	May–Sep	May–Sep	May–Sep	May–Sep
Valladolid	Mar–Oct	May–Sep	Apr–Aug	May–Sep	Jan–Dec	Apr–Oct	Apr–Oct
Germany	Mar–Oct	May–Sep	Apr–Aug	May–Sep	Jan–Dec	Apr–Oct	Apr–Oct
Santander	Mar–Oct	May–Sep	Apr–Aug	May–Sep	Jan–Dec	Apr–Oct	Apr–Oct
Turku	Jun–Aug	Jun–Aug	Jun–Aug	Jun–Aug	Jun–Aug	Jun–Aug	Jun–Aug
Sodankyla	Jun–Aug	Jun–Aug	Jun–Aug	Jun–Aug	Jun–Aug	Jun–Aug	Jun–Aug
Vardo	–	–	–	–	–	–	–

TABLE 25. MISCELLANEOUS PARAMETERS [24, 29]

Name	Unit	Value
Depth of water body	m	3
Enrichment factor		1
Turnover rate	1/a	2
Treatment factor		1
Annual sedimentation	kg/m^2 a	5
Residence time on contaminated soil	s/a	3.6E+06
Inhalation rate	m^3/a	8100
Infiltration rate	m/a	0.1
Depth of arable land soil layer	m	0.25
Depth of pasture soil layer	m	0.1
Volumetric water content sand soil	t/m^3	0.15
Volumetric water content loam soil	t/m^3	0.23
Volumetric water content clay soil	t/m^3	0.29
Volumetric water content organic soil	t/m^3	0.23
Bulk density of sand soil	t/m^3	1.5
Bulk density of loam soil	t/m^3	1.42
Bulk density of clay soil	t/m^3	1.3
Bulk density of organicsoil	t/m^3	1.35
Weathering rate constant	1/d	0.0495
Minimal weathering time	d	25

TABLE 26. CROP YIELDS [41, 42]

[kg/m² a]	Finland Turku Sodankylä	Germany Magdeburg Hannover Ulm	Italy Rome	Morocco Marrakesh	Russian Federation Rostov	Spain Santander Valladolid
Grass	0.8	0.8	0.8	0.8	0.8	0.8
Maize	4.4	4.4	4.4	4.4	4.4	4.4
Cereals	0.4	0.7	0.5	0.1	0.2	0.3
Roots and tubers	2.8	4.4	2.5	2.4	1.4	2.9
Vegetables	2.8	3.1	2.6	2.8	1.9	3.8
Fruit	2	2	2	2	2	2

TABLE 27. OTHER ELEMENT AND RADIONUCLIDE SPECIFIC PARAMETERS

Name	Source Reference	Unit	Am-243	Cl-36	Cs-135	I-129	Nb-94	Ni-59	Np-237	Pa-231	Pd-107	Pu-239	Ra-226	Se-79	Sn-126	Tc-99	Th-230	U-238	Zr-93
Concentration factor water fish	[43]	m^3/kg	2.5 E+01	5.0 E+01	1.5 E+03	5.0 E+01	2.0 E+02	1.0 E+02	1.0 E+01	2.0 E+00	1.0 E+02	8.0 E+00	1.0 E+01	2.0 E+02	3.0 E+03	8.0 E+01	3.0 E+01	2.0 E+00	2.0 E+02
Dose coefficient ingestion	[33]	Sv/Bq	2.0 E-07	9.3 E-10	2.0 E-09	1.1 E-07	1.7 E-09	6.3 E-11	1.1 E-07	7.1 E-07	3.7 E-11	2.5 E-07	2.8 E-07	2.9 E-09	7.1 E-08	6.4 E-10	3.1 E-07	4.8 E-08	1.1 E-09
Dose coefficient inhalation	[33]	Sv/ Bq	4.1 E-05	7.3 E-09	6.9 E-10	3.6 E-08	1.1 E-08	4.4 E-10	2.3 E-05	1.4 E-04	8.5 E-11	5.0 E-05	3.5 E-06	2.6 E-09	3.1 E-08	4.0 E-09	4.3 E-05	2.9 E-06	1.0 E-08
Dose coefficient external	[43]	Sv/ Bq pro Bq/ m^2	2.0 E-16	0.0 E+00	0.0 E+00	2.0 E-17	1.5 E-15	3.1 E-19	2.1 E-16	2.2 E-16	0.0 E+00	3.2 E-19	1.6 E-15	0.0 E+00	1.9 E-15	0.0 E+00	3.8 E-19	2.3 E-17	4.6 E-19
Factor for daughter nuclides	[23]		1.0 E+00	1.0 E+00	1.0 E+00	1.0 E+00	1.0 E+00	1.0 E+00	1.0 E+00	2.7 E+00	1.0 E+00	1.0 E+00	2.3 E+00	1.0 E+00	1.1 E+00	1.0 E+00	1.1 E+00	1.1 E+00	1.1 E+00
Retention factor	[44, 45]		1.0 E+00	5.0 E-01	1.0 E+00	5.0 E-01	2.0 E+00	2.0 E+00	1.0 E+00	2.0 E+00	2.0 E+00	2.0 E+00	2.0 E+00	5.0 E-01	2.0 E+00	5.0 E-01	2.0 E+00	2.0 E+00	2.0 E+00
Distribution coefficient water sediment	[46, 47]	m^3/kg	5.0 E+00	1.0 E-03	1.0 E+00	3.0 E-03	1.0 E+03	1.0 E+01	1.0 E+01	1.0 E+02	1.0 E+01	1.0 E+02	1.0 E-01	5.0 E+00	5.0 E+00	5.0 E-04	1.0 E+02	5.0 E+00	1.0 E+00
Enrichment Factor	[24]		4	1	3	1	3	1	3	3	3	3	3	1	1	1	3	3	3
Half life	[33]	a	5.7 E+03	7.4 E+03	3.0 E+05	2.0 E+06	1.6 E+07	2.0 E+04	7.5 E+04	2.1 E+06	3.3 E+04	6.5 E+06	2.4 E+04	1.6 E+03	6.5 E+04	1.0 E+05	2.1 E+05	7.5 E+04	4.4 E+09
Effective thickness	[24]	m	3.1 E-02	0.0 E+00	0.0 E+00	3.0 E-03	4.4 E-02	5.0 E-03	3.5 E-02	3.0 E-02	0.0 E+00	5.0 E-03	4.4 E-02	0.0 E+00	4.2 E-02	0.0 E+00	1.0 E-02	3.0 E-02	0.0 E+00
Transfer-factor food to milk	[23, 37]		1.0 E-06	2.0 E-02	5.0 E-03	5.0 E-03	1.0 E-06	1.0 E-03	5.0 E-06	5.0 E-06	1.0 E-03	1.0 E-06	3.0 E-04	1.0 E-03	5.0 E-04	1.0 E-04	5.0 E-06	1.0 E-04	1.0 E-06
Transfer-factor food to beef	[23, 37]		1.0 E-04	2.0 E-02	2.0 E-02	1.5 E-02	1.0 E-06	5.0 E-03	1.0 E-04	1.0 E-05	1.0 E-03	1.0 E-04	3.0 E-03	5.0 E-03	1.0 E-03	5.0 E-04	1.0 E-05	1.0 E-04	1.0 E-06
Transfer-factor food to pork	[23, 37]		3.0 E-04	3.0 E-01	4.0 E-01	3.0 E-02	3.0 E-06	1.0 E-02	3.0 E-04	3.0 E-05	3.0 E-03	3.0 E-04	2.0 E-03	1.0 E-02	3.0 E-03	1.0 E-03	3.0 E-05	3.0 E-04	5.0 E-06
Transfer-factor food to mutton	[23, 37]		1.0 E-03	3.0 E-01	5.0 E-01	3.0 E-02	1.0 E-05	5.0 E-02	1.0 E-03	1.0 E-04	1.0 E-02	1.0 E-03	5.0 E-04	5.0 E-02	1.0 E-02	5.0 E-03	1.0 E-04	1.0 E-03	1.0 E-05
Transfer-factor food to poultry	[23, 37]		6.0 E-03	2.7 E+00	2.7 E+00	8.7 E-03	3.0 E-04	9.7 E+00	7.5 E-01	7.5 E-01	9.7 E+00	2.0 E-05	1.0 E+00	9.7 E+00	7.5 E-02	1.3 E-01	7.5 E-01	7.5 E-01	6.0 E-05
Transfer-factor food to egg	[23, 37]		3.0 E-03	6.0 E+00	4.0 E-01	2.4 E+00	1.0 E-03	2.0 E-01	1.1 E+00	1.1 E+00	2.0 E-01	1.2 E-03	1.0 E+00	1.6 E-01	1.0 E+00	1.0 E+00	5.0 E-01	1.1 E+00	2.0 E-04
Transfer-factor food to reindeer meat	[23, 37]		1.0 E-04	2.0 E-02	2.0 E-02	1.5 E-02	1.0 E-06	5.0 E-03	1.0 E-04	1.0 E-05	1.0 E-03	1.0 E-04	3.0 E-03	5.0 E-03	1.0 E-03	5.0 E-04	1.0 E-05	1.0 E-04	1.0 E-06

APPENDIX II. SOIL AND PLANT PROCESSES

II.1. BACKGROUND

SG2 has focused on the way in which current models for radioactive waste management performance assessment applications deal with soil and plant transfer processes when representing alternative climate conditions. At issue is the balance between use of generic models and specific models for different conditions, and how different processes can be represented for alternate conditions within the structure of the model. With this context SG2 focuses on the representation of distinct climate states and not how the modelling of the processes is affected by the transition from one state to another.

Essentially, then, SG2 was a forum in which current model capabilities could be tested in a scenario for which they had largely been designed (representation of radionuclides transport and accumulation under temperate agricultural conditions) as well as scenarios which differed in important respects of hydrological regime and irrigation demand. The intention was to identify the modelling differences and, with contributions from some recently derived models, to discuss alternative approaches for different climate conditions.

Soil – plant interactions are a key part of modelling doses arising via the foodchain, they are common to all dose assessment models. In the past decade there has been divergence with participants in this exercise showing a range of alternative treatments of FEPs. The trend has been to balance the detailed descriptions of transport sub-models in soil and surface waters with more detailed representations of the uptake by crops.

Agricultural crops under temperate conditions are a traditional benchmark in dose assessment models. The calculations reported here were designed to consider the idea that the models developed for such conditions can be applied to other climate states by a change to parameter values, i.e. the structure of the model remains the same but the dataset changes to reflect different local conditions. The test case employed here reflects this in that local conditions (soil type, crop, etc.) are chosen to be as similar as possible with only climate conditions differing.

However, climate differences are only one feature of the difference between geographical locations. In the global context the semi-arid and arid conditions of southern Europe and northern Africa have their own geomorphological and thereby hydrological setting which is rather different to the characteristics of the northern boreal forests. These are the opposite ends of the climate spectrum in which the type of agriculture considered in this project can reasonably be practised, the role of the farmer being to maintain soil conditions in such a way as that the plants are able to thrive *despite* the hostility of the local climate.

The example calculations carried out here focus on irrigated agricultural systems and compare the pathways by which crops can become contaminated as a result of irrigation with contaminated groundwater: name by root uptake or direct foliar interception of contaminated irrigation water. The balance between the two FEPs in the model results reflects assumptions about: (a) climate; (b) crop type; and (c) local hydrology. Four of the organisations the Working have contributed results and there are therefore four distinct modelling approaches employed, see Table 28.

TABLE 28. SUMMARY OF SYSTEM PROPERTIES OF THE REFERENCE BIOSPHERE FOR THE WG3 SUBGROUP 2 MODELLING EXERCISE

Organization / Participant	Country	Modelling tools	References
SSM –Radiation Safety Authority, Stockholm R.A. Kłos, S. Xu	Sweden	Ecolego – a 10 layer soil model (GEMA-10L) with distinct solid and solute phases, dynamic plant, integrated irrigation model	[48]
SCK / CEN – Centre for Nuclear Studies, Mol G. Olyslaegers	Belgium	Hydrus 1D soil model, independent irrigation calculation	[49]
HMGU – Helmholtz Centre for Health and Environment, Munich Ch. Staudt	Germany	Ecolego 1 compartment soil model, independent irrigation calculations	[50]
CIEMAT – Centre for investigation into energy and the environment, Madrid D. Pérez-Sánchez	Spain	New 10 layer soil model with variable water table. Independent irrigation calculation	[51]

Of the models participating there are compartment models with different spatial resolution in the soil column. Two of the models are based on annually averaged parameters whereas the other two calculate water balance and moisture content on a daily basis. Results indicate that despite decades of application there is, as yet, still no firm consensus. A fine spatio-temporal discretisation of the models comes from their application to processes in response to the specific site conditions.

The use of climate analogues may be considered as a first approximation for representing system change. Results and discussion suggest that care should be taken to ensure that other factors – such as changes in hydrology and, potentially, geomorphology are also accounted for in the representation of future conditions.

To this end a simple agricultural system has been described using a common basis (irrigation of cereals on a sandy, well-drained soil). Climatological data was taken from three locations from northern Europe: Sweden – boreal conditions, Northern Germany – temperate conditions and Spanish – Mediterranean conditions.

Two additional modelling cases are considered: the first a discussion of spatial-temporal discretisation, arises from the transient application of irrigation water to soils and crops in Spain. It attempts to determine if the current method of annual averaging typically employed in contemporary models is sufficient when local conditions in the soils modelled in the test case will have saturation profiles which vary on timescales much shorter than the annual and represented in the model by monthly averages). The second discussion of spatial-temporal discretisation comes from a consideration of boreal landscape with a much shallower water table and situations are common where a contaminated aquifer used for irrigation close to the surface.

The set of modelling cases are summarized in Table 29. The case description, suggested database and requested modelling results are given in Section I.2. The models themselves are described in Section I.3 and results are presented in Section I.4.

TABLE 29. SUMMARY OF MODEL FUNCTIONALITY RELEVANT TO THE EXERCISE

Models	Boreal conditions	Temperate conditions	Mediterranean conditions	Specific site conditions
HMGU	✓	✓	✓	–
GEMA-10L	✓	✓	✓	✓
SCK/CEN	✓	✓	✓	–
CIEMAT	–	–	✓	✓

II.2. SCENARIO DESCRIPTION

II.2.1. Common characteristics

There are two main routes by which radionuclides in contaminated irrigation water can enter plant tissues: direct foliar adsorption and by uptake of activity which has reached the soil through the root system of the plant. The irrigation pathways has been the subject of many modelling exercises, the focus here is on how differences in climate conditions influence the type of model used and also the database and type of information required by the model.

With the focus on the influence of climate, the case specified here employs common features in so far as possible with only climate data differentiating the sites, thus the case considers:

- Irrigation of a cereal crop[3];
- Crop cultivated on sandy soil of depth upto 1 m (three layers 0–0.3 m, 0.3–0.6 m and 0.6–1.0 m were identified in the case specification), total irrigated area of 10^4 m^2;
- Radionuclides: ^{79}Se, ^{129}I, ^{135}Cs, ^{226}Ra and ^{238}U;
- A common set of soil kds, soil-plant transfer factors, irrigation interception factors.

The source of activity is a contaminated source of irrigation water. For the Mediterranean and temperate climates this implies an isolated deep aquifer (> 10 m) with no feedback from percolating irrigation water. An isolated lake is taken to be the source for boreal conditions[4]. The source of irrigation is isolated from the modelled system and constant concentration of 1 Bq m^{-3} is assumed.

According to the agreed format for results, the details to be provided for analysis were the radionuclide concentration in the dry weight plant and soil at times in the interval from time = 1 to time = 10^4 years, shown in Table 30 below.

[3] The basic data for the crop describes winter wheat. This crop was selected because it is known that winter wheat is cultivated in each of the climate zones. However, there was some debate about irrigation as applied to winter wheat under boreal conditions since the growth period of winter wheat coincides with long periods of sub-zero temperatures. It is assumed, therefore that any irrigation would take place during the spring months when there is a small precipitation deficit.

[4] The water table in northern European boreal climate states a close to the surface (typically within 1–3 m) and this can be used as a source of well water. Abstraction from the local aquifer can have effects on the concentration in the aquifer which propagate throughout the system in time. For this reason a contaminated lake is implied. Two additional contributions (SSM, Sweden and CIEMAT, Spain) discuss the influence of a near surface water table in Section II.4.5.

TABLE 30. FORMAT FOR TABULATION OF RESULTS

Time	Total plant concentration	Plant concentration due to foliar adsorption	Plant concentration due to root uptake	Soil concentration 0–30 cm	Soil concentration 30–60 cm	Soil concentration 60–100 cm
[a]	[Bq kg^{-1} dw]	[Bq kg^{-1} dw]	[Bq kg^{-1} dw]	[Bq kg^{-1} dw]	[Bq kg^{-1} dw]	[Bq kg^{-1} dw]
1	...	...	...	...	...	...
...	...	...	...	...	...	...
10^4	...	...	...	...	...	...

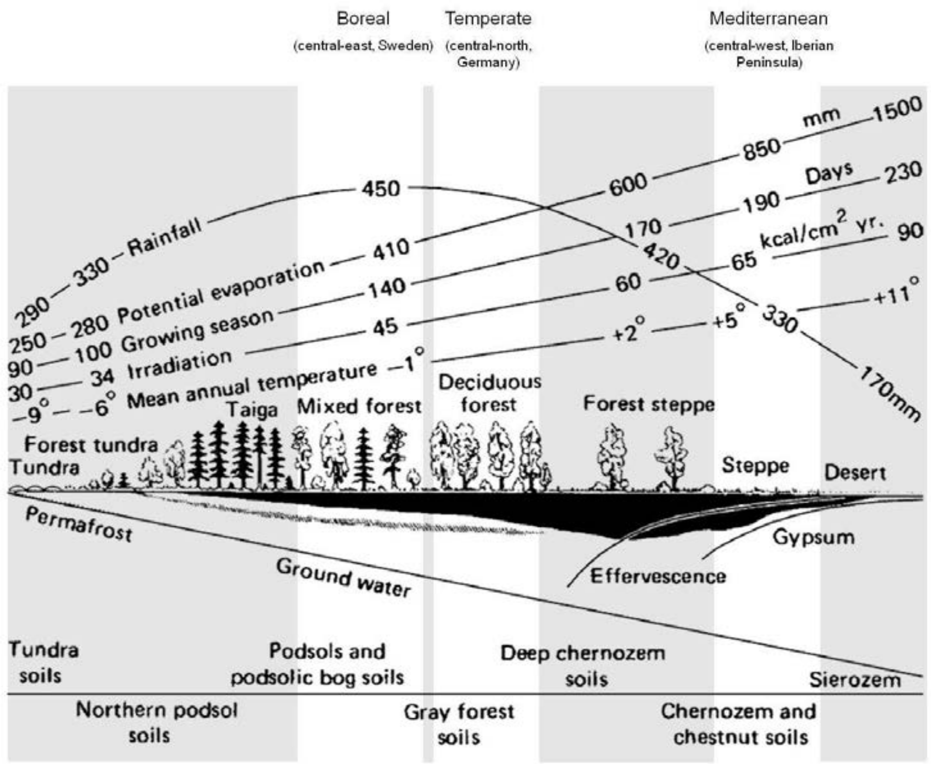


FIG. 11. Summary of climate conditions for the three sites considered in the modelling exercise [52][5].

The databases on which these fundamental site characteristics are taken describe sites in boreal, temperate and Mediterranean conditions (respectively, Sweden [53], northern Germany [50, 54] and Spain [51]. Additional information taken from these sources is directly related to climate conditions. These data are discussed, in the following sections for each climate state in turn. Figure 11 illustrates background details for each of the climate states.

The “natural” vegetation in each biome differs from the mixed forest of boreal conditions to the steppe conditions of the Mediterranean. The hydrological balance clearly differs between the three sites but winter wheat is cultivated at each of the sites from which the basic data are drawn. Although local conditions differ, farming practices mitigate the effects of natural conditions.

[5] Note: for the sake of commonality in the modelling exercise, the decision was made to consider a single soil type in each climate state. The soil types identified here are typical of the climate conditions but are not prescriptive.

Detailed site descriptive information was provided by the Helmholtz Centre, Munich, giving the description of a temperate site based on conditions in north-central Germany [50, 54]; SSM, Sweden providing details extracted from SKB's extensive site descriptive studies of the Forsmark area on, what is currently, the eastern coast of Sweden [53] and CIEMAT with information concerning Spanish conditions and practices [55, 56].

Using these sources the members of the subgroup selected the properties given in Table 31, with associated parameterization in Tables 32–34.

Participating modellers used alternative interpretations of the irrigation interception process. Data here are common to each of the climate types. As given the interpretation assumes use of either the Chamberlain formula or the model described by Bergström and Barkefors [57]. The approach is similar to that taken by Staudt et al. [54] – see Section I.4.

As the aim of the exercise was to compare the treatment of climate related factors in contemporary models only best estimate numerical values were applied. This allows the conceptual uncertainty to be fully expressed without the influence of associated data uncertainty and variability, see Table 35.

TABLE 31. ROOT FRACTION AS A FUNCTION OF PROFILE DEPTH (INTERPRETED FROM [58])

Depth [m]	Root fraction [-]
-0.10	0.29
-0.20	0.17
-0.30	0.16
-0.40	0.14
-0.50	0.09
-0.60	0.06
-0.70	0.05
-0.80	0.02
-0.90	0.01
-1.00	0.01

TABLE 32. DATA CHARACTERIZING IRRIGATION INTERCEPTION

Parameter	Units	Value	Reference
Mass interception factor	[m^2 kg^{-1}]	0.66	[59]
Weathering half-life	[days]	15	[57]
Retention of irrigation water	[m^3 m^{-2}]	0.003	
Translocation factor (root crops)	[(Bq kg^{-1} ww) (Bq m^{-2})$^{-1}$]	0.1	
Storage capacity	[m^3 m^{-2}]	0.0003	
LAI (all vegetables)	[m^2 m^{-2}]	5	
Element dependent retention factor: Anions	–	0.5	
Cations	–	2	
Cs	–	1	

NOTE: Participating models used alternative interpretations of the irrigation interception process. Data here are common to each of the climate types. As given, the interpretation assumes use of either the Chamberlain formula or the model described in [57]. The approach is similar to that taken in [54] – see Section I.4.

TABLE 33. SUMMARY OF SYSTEM PROPERTIES OF THE REFERENCE BIOSPHERE FOR THE WG3 SUBGROUP 2 MODELLING EXERCISE

Property	Description
Soil type	Sand – common to all three regions studied.
Topography	locally low relief, cultivated land implicitly on a area of level ground.
Drainage and water content	Precipitation and irrigation are assumed to drain through the base of the soil. The water table is assumed to lie between 1 m and 0.5 m from the surface, dependent on local conditions.
Crop type	Cereals – Winter wheat is cultivated at each of the three climate zones featured.
Irrigation source	Constant concentration remote source (unconnected aquifer or lake).

TABLE 34. PARAMETERS AND VALUES FOR COMMON CHARACTERISTICS

Parameter	Unit or radionuclide	Value	Reference
Area of cultivated land	[m^2]	10^4	Defined
Soil depth	[m]	1	Defined
Soil mineral density	[kg m^{-3}]	2650	http://webmineral.com/data/Quartz.shtml
Soil porosity	[-]	0.4	http://web.ead.anl.gov/resrad/datacoll/porosity.htm
Soil solid – distribution coefficient, K_d [litre kg^{-1}]	^{79}Se	56	[23]
	^{129}I	4	
	^{135}Cs	530	
	^{226}Ra	3100	
	^{238}U	110	
Soil – plant transfer factor, K_p [(kg^{-1} dw soil) (kg^{-1} dw plant)$^{-1}$]	^{79}Se	0.19	[23]
	^{129}I	0.00063	
	^{135}Cs	0.039	
	^{226}Ra	0.017	
	^{238}U	0.0089	

NOTE: as the aim of the exercise was to compare the treatment of climate related factors in contemporary models only best estimate numerical values were applied. This allows the conceptual uncertainty to be fully expressed without the influence of associated data uncertainty and variability.

II.2.2. Temperate conditions

Consistent with Figure 11, temperate conditions in this intercomparison are taken from the Gorleben site central-north Germany. The area is characterized by relatively cool summers and relatively mild winters. A characterisation of the climate by mean monthly and annual temperature and precipitation is given in Table 35. Primary data were measured at the station Lüchow, some 20 km to the southwest (53° N, 11° E). The maximum of the monthly average temperature is below 22°C, and more than 4 months have a monthly average temperature of around 10°C.

The area considered belongs to the dryer areas of Germany and though no detailed are available for evapotranspiration there is known to be a principal water deficit during vegetation period, amounting to around 100 mm [60]. Olyslaegers [59] has used Hargreaves's equation [61] to evaluate the potential evapotranspiration. Actual evapotranspiration was interpreted using the data from the FAO [62] and the monthly values quoted here are an interpretation[6] of this and are consistent [63]. The calculated irrigation requirement is thus 128 mm a^{-1}. This is interpreted in this dataset as being applied in four irrigation events in each of the months April, May, June and July.

[6] In practice the models used by most of the participants did not use the monthly data provided here, employing only the annual data. The numerical data here are included for completeness.

TABLE 35. CLIMATE DATA FOR TEMPERATE CONDITIONS

Month	Temperature °C	Precipitation [mm a^{-1}]	Evapotranspiration Potential (calculated) [mm a^{-1}]	Evapotranspiration Actual (implied) [mm a^{-1}]	Assumed irrigation [mm a^{-1}]
January	-0.2	39	8	8	
February	0.2	31	14	14	
March	3.3	33	35	20	
April	7.5	38	64	64	46.25
May	12.4	50	100	58	46.25
June	16.1	62	128	66	46.25
July	17.1	71	121	71	46.25
August	16.7	64	105	39	
September	13.4	43	62	26	
October	9.4	37	30	30	
November	4.6	42	12	12	
December	1.6	46	6	6	
Total		556	685	415	185
Average	8.5	46.3			
Balance		326			
Reference / comments	Records from the Lüchow met. Station, Germany, representative of the Gorleben region [50]		Calculated using Hargreaves's formula [59]	Interpreted from [62]. Consistent with values for Copenhagen [63]	Four equal events assumed

The natural vegetation of the biome is temperate evergreen forests and nemoral broadleaf-deciduous forests. Due to the sandy soils, pine trees and birches dominate but agriculture is also a feature of the managed environment. Crop production typically includes barley, wheat, sugar beet, potatoes, maize, pasture gardening for home consumption. From this list winter wheat is selected. Parameters characterizing growth are listed in Table 36.

II.2.3. Boreal conditions

Details for the boreal climate are based on the area around 60° N, 18° E, at Forsmark on the eastern coast of Sweden [64]. The winters are colder than in the boreal case and while, coincidentally, the precipitation and actual evapotranspiration amounts are similar to the temperate case, the potential evapotranspiration is substantially less. The overall irrigation requirement is therefore less than in temperate dataset. This serves to focus attention on the irrigation component of the soil-plant system. Table 37 gives the basic details for boreal conditions in the exercise.

The natural vegetation of the biome is mixed forests and there are extensive areas of woodland and lake ecosystems but there are important agricultural regions and winter wheat is part of the agricultural mix in the region. There is invariably snow cover during the winter months but there is, nevertheless, an precipitation deficit in the spring. It is therefore assumed that there will be is irrigation in each of the 4 months from April to July. Harvest is at the end of July. Table 38 summarizes the agricultural practices.

TABLE 36. CROP SPECIFIC PARAMETERS (APPROPRIATE FOR WINTER WHEAT) FOR THE TEMPERATE CLIMATE

Parameter	Unit	Value	Reference/comment
Crop yield	[kg m^{-2} a^{-1}]	0.5	[65]
Biomass production	[kg m^{-2} a^{-1}]	1	yield × 2
Irrigation period	months	4	
Number irrigation events	[events a^{-1}]	4	once per month
Total irrigation	[mm a^{-1}]	185	
Irrigation per event	[mm $event^{-1}$]	46.25	

TABLE 37. CLIMATE DATA FOR BOREAL CONDITIONS

Month	Temperature °C	Precipitation [mm a^{-1}]	Evapotranspiration		Assumed irrigation [mm a^{-1}]
			Potential (calculated) [mm a^{-1}]	Actual (implied) [mm a^{-1}]	
January	-1	43	2	2	
February	-2	32	6	6	
March	-3	29	22	22	
April	3	34	39	39	25
May	8	26	65	54	25
June	13	38	118	67	25
July	18	70	121	101	25
August	18	65	88	69	
September	13	60	29	29	
October	8	52	18	18	
November	3	60	3	3	
December	0	49	1	1	
Total		558	511	410	100
Average	6.5	46.5			
Balance		147			
Reference / comments	For Forsmark [64]. (Annual actual irrigation quoted, monthly values interpreted from [62])				Four equal events assumed

TABLE 38. CROP SPECIFIC PARAMETERS (APPROPRIATE FOR WINTER WHEAT) FOR THE BOREAL CLIMATE

Parameter	Unit	Value	Reference
Crop yield	[kg m^{-2} a^{-1}]	0.5	[64]
Biomass production	[kg m^{-2} a^{-1}]	1	yield × 2
Irrigation period	months	4	Table 37
Number irrigation events	[events a^{-1}]	4	once per month
Total irrigation	[mm a^{-1}]	100	Table 37
Irrigation per event	[mm $event^{-1}$]	25	Table 37

II.2.4. Mediterranean conditions

The Mediterranean site is characterized by the data that correspond to a site in the central-west of the Iberian Peninsula (39° N, 6° W). The typical climate of the region is temperate Mediterranean - maritime Mediterranean or mild winters. At regional scale its extension is about an area of 10 km radio and 50 km^2 at local scale. Potential evapotranspiration (ETP) obtained by Thornwaite method, for a medium year, is 831.4 mm a^{-1}. The actual evapotranspiration (ETR), obtained using the Turc method [66] empirically relate the precipitation and the mean annual temperature with the potential evapotranspiration. The results imply a value of 582 mm a^{-1}, implying a scaling factor of 0.7 which is applied to each of the monthly potential evapotranspiration values.

The groundwater flow varies at different depths. Close to the surface, the water is mainly due to rainfall infiltration through the superficial units (lehms or granite). It is therefore reasonable to assume that the local hydrology can be described as infiltration and percolation with actual evapotranspiration closely related to applied irrigation. This is reflected in the basic dataset for the intercomparison. The sandy soil assumed promotes rapid drainage and is consistent with the basic assumptions for the site. However, the database deployed [51] discusses a location where the groundwater table is somewhat loser to the surface.

The ecosystem is classified as steppe or prairie. These are areas of bush and grassland. With irrigation, wheat and other arable corps can be cultivated, though with reduced yields compared to temperate/boreal conditions (Table 40).

II.2.5. Summary of irrigation requirement and source terms

The requirement for irrigation varies from 100 mm a^{-1} to 209 mm a^{-1}. As indicated, irrigation is spread out during the year so that there are a number of irrigation events. For simplicity it is assumed that they each deliver an equal amount of water. Boreal and temperate conditions have 4 events (25 and 46.25 mm per event, respectively) and Mediterranean conditions imply 8 events each delivering 21.6 mm. In this way the amount of activity entering the system is determined by the climate conditions to be the product of total irrigation, total area and concentration of irrigation water:

- Boreal $0.100 \times 10^4 \times 1.0 = 1.00 \times 10^3$ Bq a^{-1},
- Temperate $0.185 \times 10^4 \times 1.0 = 1.85 \times 10^3$ Bq a^{-1},
- Mediterranean $0.209 \times 10^4 \times 1.0 = 2.09 \times 10^3$ Bq a^{-1}.

II.3. II.3 MODEL DESCRIPTIONS

II.3.1. Overview

There are two distinct processes by which radionuclides in irrigation water can become integrated in plant tissues. The first is direct foliar interception and the second is uptake via the roots' interaction with radionuclides accumulated in soil. Each of the models employed by the participating organisations implement these processes though there are key differences relating to the structure and spatial discretisation of the soil and the way in which interception is parameterized. The model representations are briefly described below. The key modelling differences are further addressed in Section II.3.6.

TABLE 39. CLIMATE DATA FOR MEDITERRANEAN CONDITIONS

Month	**Temperature °C**	**Precipitation [mm a^{-1}]**	**Evapotranspiration**		**Assumed irrigation [mm a^{-1}]**
			Potential(calculated) [mm a^{-1}]	**Actual (implied) [mm a^{-1}]**	
January	91.4	13.7	7.4	9.6	
February	75.8	17.7	8.6	12.4	
March	55	34.1	11.3	23.9	26.1
April	61.4	46.4	13.1	32.5	26.1
May	47.1	80.2	17.1	56.1	26.1
June	25.9	122.3	22	85.6	26.1
July	5.4	160.7	25.7	112.5	
August	4.7	149.5	25.6	104.7	
September	30.3	104.4	22.2	73.1	
October	74.5	60.3	16.6	42.2	
November	92.3	27.3	11.2	19.1	
December	92.5	14.8	7.9	10.4	
Total	656.3	831.4	188.7	582	209
Average	54.5	69.3			
Balance		33.9			
Reference / comments	Monthly and annual average temperatures, precipitation and evapotranspiration for a 43 years period (1961–2003) of records in Alcuéscar station. Additional details from reference [51].				Eight equal events assumed.

TABLE 40. CROP SPECIFIC PARAMETERS (APPROPRIATE FOR WINTER WHEAT) FOR THE MEDITERRANEAN CLIMATE

Parameter	**Unit**	**Value**	**Reference**
Crop yield	[kg m^{-2} a^{-1}]	0.3	
Biomass production	[kg m^{-2} a^{-1}]	0.6	yield × 2
Irrigation period	months	4	
Number irrigation events	[events a^{-1}]	8	twice per month
Total irrigation	[mm a^{-1}]	209	
Irrigation per event	[mm event^{-1}]	25	

TABLE 41. SUMMARY OF KEY CLIMATE FEATURES RELEVANT TO THE SYSTEM MODELLING

Feature	**Parameter**	**Unit**	**Climate state**		
			Boreal	**Temperate**	**Mediterranean**
Water fluxes	Annual precipitation	[mm a^{-1}]	558	556	656.3
	Annual actual ETP	[mm a^{-1}]	410	415	581.98
	Irrigation requirement	[mm a^{-1}]	100	185	209
Temperature	Mean annual	C	6.5	8.5	15.7
	Min monthly average	C	-3.0	-0.2	7.4
	Max monthly average	C	18.0	17.1	25.7
Crop properties and requirements	Irrigation period	[-]	April–July	April–July	March–July
	Number of irrigation events	[a^{-1}]	4	4	8
	Crop yield	[kg dw m^{-2} a^{-1}]	1	1	0.6

II.3.2. SSM, Sweden – GEMA-10L

The model features a ten-layer soil model with each layer representing 0.1 m of the total 1 m soil column. A compartment model, each layer is linked by transfer processes represented by first-order linear transfer coefficients and water and solid material are treated as distinct compartments. Water fluxes are the dominating transport mechanisms with evapotranspiration working throughout the column contributing to the turnover of radionuclides in the column. Precipitation and irrigation enter the system from above and the excess draining from the layer just above the permanently saturated zone due to drainage emplaced by the local community on the otherwise saturated medium in order to make agriculture possible in the otherwise saturated conditions [67].

Soil characteristics vary within the soil column so that each layer can have a specified porosity, water content and k_d, as well as density. In this way the redox state of the soil can influence the accumulation of redox sensitive radionuclides, thought he k_d values used in the case as defined are all representative of well drained and therefore oxic conditions. The active biomass (in terms of vertical transport of radionuclides) is also specified for each soil layer and this contributes to mixing within the column.

Plants interact with the soil via root uptake and this is determined from the overall root uptake factor combined with the root distribution fraction so that uptake can take place at different amounts from different layers. Foliar interception means that a fraction of the contaminants falling on the leaves as irrigation deposition is intercepted directly by the plant. The remainder is assumed to enter the upper layer of the soil column.

The model was implemented using the Ecolego model platform [68] and further details are given in [48].

II.3.3. SCK/CEN, Belgium – HYDRUS-1D

The soil model used by SCK/CEN is Hydrus-1D. Hydrus-1D is a public domain Windows-based modelling environment for analysis of water flow and solute transport in variably saturated porous media. The software package includes the one-dimensional finite element model HYDRUS for simulating the movement of water, heat, and multiple solutes in variably saturated media. The model is supported by an interactive graphics-based interface for data-pre-processing, discretisation of the soil profile, and graphic presentation of the results.

In comparison to a classical compartmental model this computer code numerically solves the Richards-equation for variably-saturated water flow and convection-dispersion type equations for heat and solute transport. Additionally the flow equation incorporates a sink term to account for water uptake by plant roots. The governing flow and transport equations are solved numerically using finite element schemes [49]. As applied here, the model was used to calculate transport of the radionuclides through the vadose zone (unsaturated) following different irrigation events with contaminated irrigation water. The unsaturated soil hydraulic properties are described [69, 70] and modified van Genuchten type analytical functions. Irrigation (and precipitation) events are considered on a daily basis. As an output, the distribution of radionuclide concentration in the soil was calculated as the product of this soil concentration and the specified soil-plant transfer factor in Table 34. Foliar interception assumes an interception fraction based upon the mass interception coefficient given in Table 32.

II.3.4. HMGU, Germany

The model used by HMGU is a straightforward compartment model with a single well mixed compartment representing the top 25 cm of the soil. The k_d values is used to calculate the retardation factor and this is used to calculated retention in the compartment in response to the balance between precipitation, irrigation and evapotranspiration. The content of the crop due to root uptake is calculated using the soil-plant transfer factor from Table 34 based on the derived soil concentration. Foliar interception is calculated using a method based on [28] and full details are described elsewhere [54].

II.3.5. CIEMAT, Spain

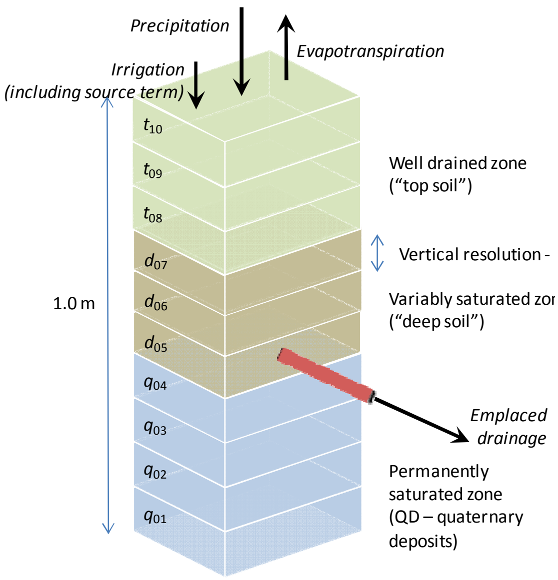
A key concern in Spain is the variation of the water table height and the CIEMAT model implements a time-varying water table. Ten layers in the soil model are modelled and the water content of the individual layers therefore varied in time on a temporal scale of months. A dynamic plant compartment is also included. The model [51] was originally constructed to represent selenium transport and accumulation in soils and therefore takes into account variation in sorption as a function of water saturation and local redox conditions in each of the layers. As used here, this newly developed model was reconfigured and run for ^{238}U and ^{226}Ra only for Mediterranean conditions.

II.3.6. Key modelling differences

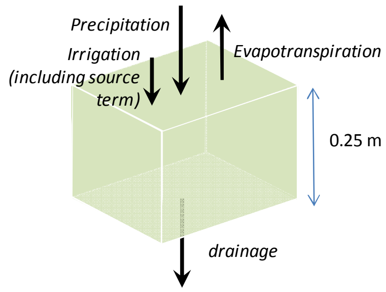
II.3.6.1. Structure of the soil mode and water balance

Figure 12 shows the model structures used in the soil-plant systems modelling exercise. Two models employ a similar structure in that they each have 10 layers and explicitly address the variably saturated zone, albeit with different interpretations of the processes involved. One model is a more traditional single compartment model and the fourth model uses a more detailed model with a finite element representation. In terms of these structures the drainage system is a key interpretational difference. The GEMA-10L model reflects practice in Scandinavia where wetlands (with high water tables) are drained to allow agriculture. Because the Quaternary deposits lie on top of crystalline bedrock there can be no drainage from the base of the column and the emplaced drainage is essential to maintain suitable soil conditions. This configuration is maintained in the case of temperate and Mediterranean conditions since it is assumed that the site remains in the same geographical location during periods with altered climate conditions. The other models all assume natural drainage at the base of the column.

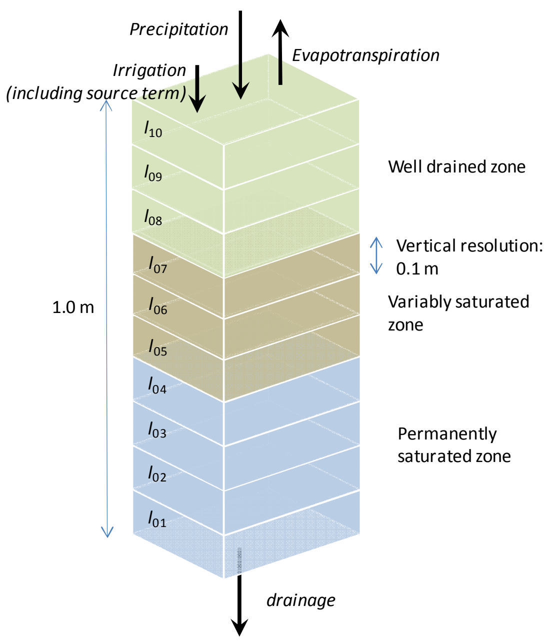
The position of the water table is important in determining the distribution of radionuclides in the soil column and topography as well as climate plays a key role. In the modelling carried out in this subgroup, the source of irrigation water is implicitly isolated from the soil's hydrology. Irrigation acts as a back-up for a precipitation short-fall and the source is external to the soil system; it enters at the top of the soil column and drains through the column through the lower boundary. Contaminants in the irrigation water interact with the constituents of the soil in the way through.



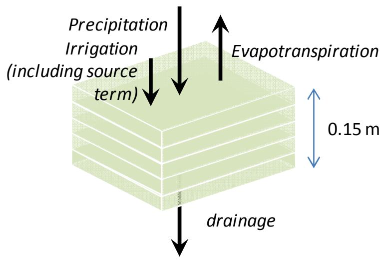
(a) SSM – 10 layers (20 compartments), emplaced drainage ~ 55 cm below the surface



(b) HMGU – single soil compartment, natural drainage at base



(c) CIEMAT – 10 compartments, natural drainage at base. Dynamic plant compartment (not shown)



(d) SCK/CEN - 100 layers in a finite element representation, natural drainage at base distributed over a length of 1 m depth

FIG. 12. Structure of the models used in the soil-plant systems investigation.

In temperate and Mediterranean regions of Europe the situation is common that the water table is several metres below the surface and capacity of the aquifer is great enough that recharge from percolating infiltration plus irrigation can be considered negligible. Locations with significant relief are representative of the scenario. In boreal Europe relief can be much shallower and situations are common where a contaminated aquifer used for irrigation is close to the surface, with to potential recirculation from aquifer to soil surface with percolation back to the aquifer. Maintaining constant concentration in the irrigation source within the model is difficult. To represent this boundary condition is a realistic way it can be assumed that a lake is the source of irrigation water under boreal conditions. The case of shallow aquifer and is briefly discussed in Section II.4.5 in the context of the Swedish landscape, where both near surface aquifers and lakes are used in agriculture.

As described here, precipitation and irrigation water, less ETP percolates through the soil column. The fraction retained in the soil is determined by the k_d. Each of the models implements an effective loss term due to percolation equivalent to:

$$\lambda_{loss} = \frac{P + I - E}{\theta l R} \ [\mathrm{a}^{-1}] \quad \text{(II.1)}$$

with precipitation, irrigation and evapotranspiration amounts respectively P, I and E [m a^{-1}]. The thickness of the soil is l [m] and the volumetric moisture content is θ [-]. The retardation factor, R [-], is given by:

$$R = 1 + \frac{\rho_b}{\theta} k_d \ [-] \quad \text{(II.2)}$$

where ρ_b [kg dw m^{-3}] is the dry weight bulk density of the soil and the solid-liquid distribution coefficient in the soil is k_d [$\mathrm{m}^3\ \mathrm{kg}^{-1}$].

As specified, the soil column is assumed to be 1 metre thick. Drainage is from the base of this soil layer. Some participants treat the soil as a single layer (HMGU [50]) whereas CIEMAT [51] and GEMA-10L each have 10 layers in a first-order linear kinetics approach. Each addresses the seasonal variation in water table height though with different implementations. The Hydrus-1D model used by SCK-CEN takes a more holistic approach [49] to water and contaminant transport in the column, employing a one-dimensional finite element model, HYDRUS, for simulating the movement of water, heat, and multiple solutes in variably saturated media. In contrast to the classical compartment model approach HYDRUS numerically solves the Richards-equation for variably-saturated water flow and convection-dispersion type equations for heat and solute transport. Additionally the flow equation incorporates a sink term to account for water uptake by plant roots. As applied here, the code is used to model contaminant transport through the vadose zone (unsaturated) following different irrigation events with contaminated irrigation water. The unsaturated soil hydraulic properties are described [69, 70] and modified van Genuchten type analytical functions. Irrigation (and precipitation) events are considered on a daily basis.

GEMA-10L evaluates water and solid material transport independently in each of the 10 layers of the soil model, mass balance in each layer requiring a difference similar to Equation (II.1). With its focus on specifically Scandinavian conditions – local hydrology as well as climate – GEMA-10L assumes that the water table is close to the surface and, following common agricultural practice, a drainage system is emplaced at 0.5 m depth. Drainage in the SSM boreal model is therefore at this level with saturated conditions below this depth. Bioturbation therefore only takes place in the unsaturated zone.

The CIEMAT model is designed to represent a near-surface water table and so take into account hydrochemical speciation of redox sensitive radionuclides.

II.3.6.2. Foliar interception

A fraction of the incident water is assumed to be intercepted by the foliage of the plant and the radionuclides in solution are then incorporated into the plant through foliar adsorption and translocation to other parts of the plant. The key features are: the intercepted fraction (f_x [-]), the translocation factor (T_p [-]) the weathering loss rate from external surfaces, λ_w [a^{-1}], senescence, λ_p [a^{-1}]) and the period during which irrigation takes place and the interval between irrigation and harvest (respectively τ_{irri} [a] and τ_h [a], though these intervals are of less concern for the long-lived radionuclides considered here). In generic terms, then, the concentration in the crop is calculated as:

$$C_{p,fol} = \frac{1 - \mathrm{e}^{-(\lambda_w + \lambda_p + \lambda_0)\tau_{irri}}}{(\lambda_w + \lambda_p + \lambda_0)Y_p} \mathrm{e}^{-(\lambda_w + \lambda_p + \lambda_0)\tau_h} T_p f_x C_{irri} I_{irri} \text{ [Bq kg}^{-1}\text{ dw]} \quad \text{(II.3)}$$

where, Y_p [kg dw m^{-2} a^{-1}] is the yield of the crop, C_{irri} = 1 Bq m^{-3} is the assumed concentration in irrigation water (constant for each of the climate states considered) and I_{irri} [m^3 m^{-2} a^{-1}] is the climate dependent irrigation requirement.

Each of the participating models implement Equation (II.3) in one form or another. GEMA-10L implements a dynamic plant as part of the compartment structure, neglects weathering, but includes translocation factor and is the only model to represent plant senescence explicitly. The CIEMAT and SCK/CEN models conservatively set the translocation factor to unity. The HMGU model includes translocation but not weathering. However, the main factor differentiating the participating models is the treatment of the intercepted fraction. CIEMAT take f_x = 0.5 and SCK/CEN assume f_x = 0.66, whereas the HMGU model assumes:

$$f_x = \frac{LAI_p k_p S_p}{I_{irri}} \left[1 - \mathrm{e}^{-\frac{\ln(2)}{3k_{r,p}S_p} I_{irri}} \right] \text{ [-]} \quad \text{(II.4)}$$

so that the fractional retention of the radionuclide in the irrigation water depends on the leaf area index, LAI_p [m^2 m^{-2}], the nuclide-dependent retention factor, k_p [-] and the storage capacity of the foliage S_p [m^3 m^{-2}], essentially the thickness of the film of water that can build-up during the irrigation event.

GEMA-10L assumes a similar intercepted fraction:

$$f_x = N_{irri} \frac{LAI_p k_p S_p}{I_{irri}} \text{ [-].} \quad \text{(II.5)}$$

Given that the storage capacity is 3×10^{-3} m with a retention factor of 0.5 (anions), 2 (cations) and 1.0 (cæsium) the term in brackets in Equation (II.4) is equal to 1.0 so the main difference between Equations (II.4) and (II.5) is that the latter treats irrigation as a series of independent events whereas the former takes the total irrigation as an average applied in a single application. In this way, because the fraction of water involved in the interaction with the plant is restricted to the volume coating the leaves during each event, Equation (II.5) can lead to N_{irri} times the amount involved if irrigation is treated as a single event. This may be anticipated to be important in climate states requiring multiple irrigation events to maintain crop viability.

II.3.6.3. Root uptake

The models solve for the distribution of contaminants in the soil column giving the concentration in the soil column. The concentration in the crop is then calculates by root uptake by use of the soil-plant transfer factor K_p (Bq kg^{-1} dw crop)(Bq kg^{-1} dw soil)$^{-1}$. Allowing for varying root fractions (r_i [-]) in the different soil layers, the plant concentration due to root uptake is:

$$C_{p,ru} = K_p \sum_{\substack{soil \\ layers,i}} r_i C_i \text{ [Bq kg}^{-1}\text{ dw]} \qquad \text{(II.6)}$$

where C_i [Bq kg^{-1} dw] is the soil concentration in the i^{th} layer.

HMGU models a single layer of soil 25 cm thick and SCK-CEN model 1 m as a continuum. GEMA-10L uses the distribution of roots defined in Table 31. The CIEMAT approach is somewhat more sophisticated in that root uptake is treated as a dynamic process[7] with a transfer rate from the i^{th} soil layer:

$$\lambda_{pi} = \rho_{ri} A_f l_i K \text{ [a}^{-1}\text{]} \qquad \text{(II.7)}$$

where:

ρ_{ri} (m root per m^3 soil) is the length of fine roots in soil layer *i*;
l (m) is the depth of layer i;
A_f (1 m^2) is the model area;
K (m^{-1} y^{-1}) is a normalization coefficient defined as the fractional uptake rate per unit length of fine roots.

II.3.6.4. Interpretation of alternative climate conditions

The HMGU, SCK-CEN and GEMA-10Lmodels were applied to each of the climate states described. Of these only the SCK-CEN model was able to make use of the monthly data provided, however the results were restricted to the annually time points suggested in the case specification so inter-annual variation in the outcomes was not seen. The CIEMAT model was able to make use of the time-varying climate data and this is reflected in the results discussed in Section II.4.5. The HMGU and GEMA-10L models used annual average data for the hydrologic parameters governing radionuclide transport.

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[7] Dynamic root uptake is an option in GEMA-10L but it was found to be difficult to reconcile the soil-plant transfer factors in the case specification with the dynamic case where the roots interact directly with the soil porewater. For this reason the alternative, more conventional approach to root uptake was adopted for the current project. The problem arises because the quoted transfer factors relate bulk activity on plant material to that in the soil on which the crop is cultivated. The alternative model would require transfer factors based on the plant concentration related to soil porewater concentration

The models were therefore readily configured to represent alternative climate conditions but it could be argued that the temporal resolution of the model output should be better investigated in order to verify the correct functioning of the models. Thought the results in the following section show close agreement this may be a consequence of the relatively simple biosphere system described.

II.4. RESULTS AND DISCUSSION

II.4.1. Activity concentration in soil

The quantities identified in Equations (II.3) and (II.6) are used to investigate the climate impact of the soil-plant system. For reference the time dependence of the soil concentration treated as a single compartment is shown in Figure 13. Results from the different participating models show similar dynamics, though not exactly the same. Nevertheless, this simple one compartment approximation is useful in describing the scope of the system response to constant input to the soil surface in irrigation water.

The first point of interest is that the concentration in the soil takes time to reach equilibrium. For ^{129}I, with $k_d = 4.1\times10^{-3}$ m^3 kg^{-1} reaches steady state after only before 100 years whereas the moderately sorbing nuclides ^{79}Se and ^{238}U (5.6×10^{-2} and 1.1×10^{-1} m^3 kg^{-1}, respectively) need 1 to 2 ka years of continuous input to reach equilibrium. The two most strongly sorbing species (^{135}Cs and ^{226}Ra, 0.53 and 3.1 m^3 kg^{-1}) are not quite in equilibrium in the soil until around 10 ka. It can be questioned whether it is realistic to assume constant utilisation as agricultural land, let alone continuous irrigation, of the same area on such long timescales.

Compared to the initial values of the concentration in soil, the increase over time accounts for around one and a half orders of magnitude for ^{129}I, two and a half for ^{79}Se and ^{238}U and just over three for ^{135}Cs and ^{226}Ra. In comparing the results from the root uptake pathway and the foliar interception root it is important to realise that plant concentrations by root uptake could be a small fraction of the maximum value that could arise in the case that chronic irrigation is assumed. Nevertheless the maximum, or steady-state soil concentrations are of interest and results from each of the contributions are plotted in Figure 14.

Largely dependent on k_d, the results show similar trends. There is a progressively higher soil concentration in each of the climate states as warmer conditions require increased irrigation. Comparison between the 10 soil layers of the SSM model and the single compartment of the HMGU model shows that the simpler structure retains more activity. This has been traced to the influence of bioturbation which, in the SSM model, acts to redistribute activity from the surface layer to deeper levels. The range between the models is around a factor of 5–10.

The HYDRUS results from CEN/SCK are similar for each of the radionuclides, k_d values notwithstanding. The results indicate a similar magnitude to the weakly sorbing ^{129}I for each of the radionuclides considered. The reason for this is not understood. However, the CIEMAT results for ^{238}U are similarly low (in contrast to the high k_d result for ^{226}Ra which is similar to those calculated by the other models). A possibility to be considered is that the daily variation in water content in the models is implicated somehow but this cannot be confirmed with the available results. One other curiosity is that there is apparently less accumulation in the case of the Mediterranean climate despite there being a greater input of contaminants. Again, details of the hydrology are implicated.

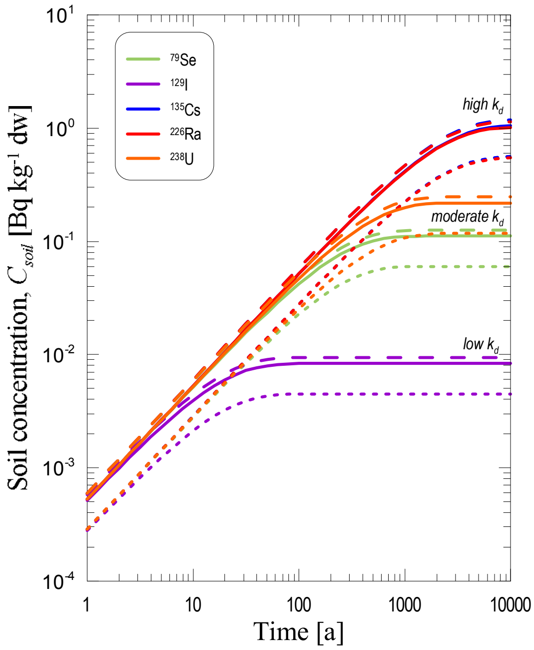


FIG. 13. Illustration of the dynamics of the soil concentration for the 5 nuclides and irrigation in the three different climate conditions. Single soil compartment model employed to illustrate the timescales involved in the irrigation model. Solid lines denote temperate climate, dots, boreal and dashes Mediterranean.

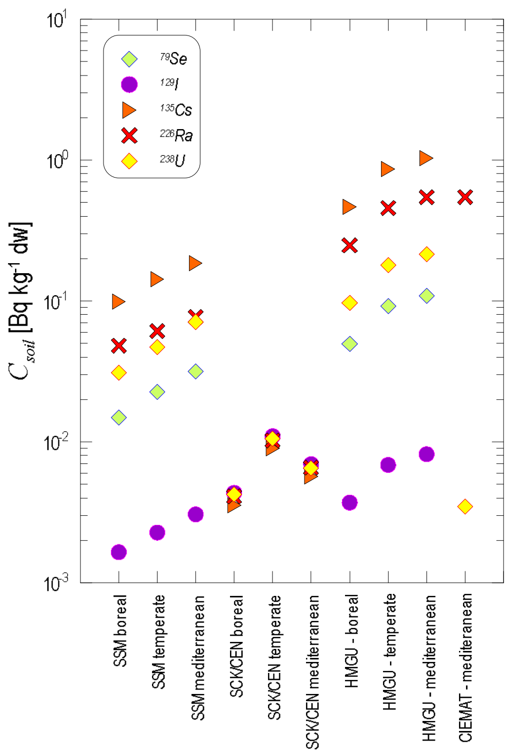


FIG. 14. Contributed maximum soil concentration for the 5 radionuclides considered, results from each of the 4 participants.

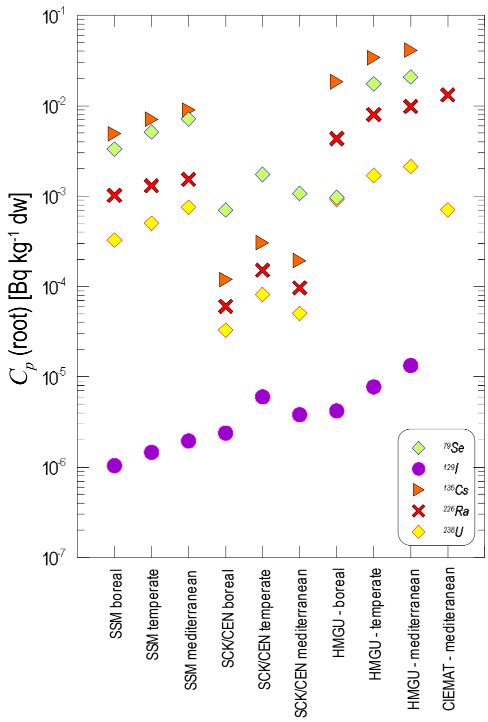


FIG. 15. Contributed maximum plant concentration via root uptake. In comparison to Figure 16 the role of root uptake is clearly indicated here, particularly in the case of the CIEMAT results where the relatively low ^{238}U soil activity concentration is compensated by relatively high root uptake, leading to comparable results for this radionuclide.

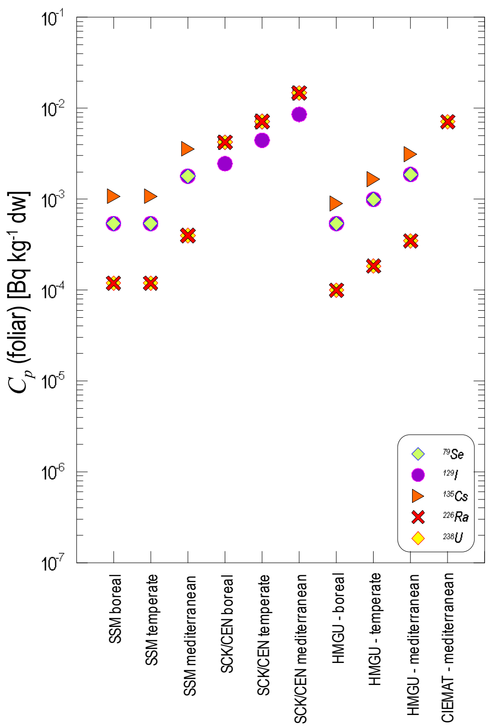


FIG. 16. Contributed maximum plant concentration via foliar interception. (NOTE: common scales are used for this plot and for the root uptake concentration above).

II.4.2. Root uptake

Derived from the soil concentration, the maximum plant concentration via root uptake calculated by the participants are plotted in Figure 15.

The role of the soil-plant transfer factor is seen in translating the soil concentration into the crop concentration. As modelled by all contributors except CIEMAT, the relation between soil and plant is a simple constant. The dynamics follow those of the soil concentration in Figure 13. The single compartment in the HMGU model produces higher concentrations than the multi-layer GEMA-10L.

The low concentration in the soil of the weakly sorbing ^{129}I corresponds with relatively low concentration in the plant. However, the high root uptake factor for ^{79}Se combines to make ^{79}Se the most highly concentrated nuclide in the GEMA-10Lcalculations, despite the relatively low soil concentration. For HMGU, ^{135}Cs has the highest concentration by root uptake.

The CIEMAT model has a dynamic plant and so the evolution of the crop concentration does not necessarily parallel that of the soil concentration for the two radionuclides evaluated here. Interestingly, where the maximum soil concentration was lower, the modelling of root uptake in gives rise to similar values for plant concentration to those of the GEMA-10L and HMGU Mediterranean climate models.

II.4.3. Foliar interception

Derived from the concentration of radionuclides in the irrigation water, the maximum plant concentration via foliar adsorption calculated by the participants are plotted in Figure 16. The soil concentration builds up slowly in time (Figure 13) so that irrigation over of the same agricultural area is required to approach the maximum plant concentration via root uptake. There is no such requirement for foliar adsorption and these maximum concentrations are reached in each annual growth cycle of the crop.

These results emphasize the potential importance of the foliar interception pathway to long term waste disposal assessments. While root uptake takes time to reach its maximum effect, irrigation interception is soon at a maximum impact, there is an increasing likelihood of irrigation being required in warming climates. Furthermore irrigation sources can be linked to the deeper geosphere as a way of bypassing the near surface geology and thereby avoiding further dilution in the near-surface environment.

Although all participants employed variants of Equation (II.3) in the calculation of foliar adsorption, the variations seen in Figure 16 can be understood in differences in the interpretation of the interception fraction f_x in Equations (II.4) and (II.5).

There are 4 sets of results for irrigation interception and these are all calculated on a common basis, albeit with different interpretation and alternative assumptions. The highest results are calculated by the SCK-CEN and CIEMAT models. A feature here is that the SCK-CEN model does not include a translocation factor and assumes a relatively high value for the mass-interception coefficient of 0.66, which corresponds to an interception fraction of $f_x = 0.4$. The CIEMAT model assumes that 50% of the incident water is intercepted and retained. The key to understanding the difference in the results here is that the intercepted fraction represents the activity which is available to the plant on the leaf surfaces. Neither of these two models includes a *translocation factor* which would account for differential accumulation of activity in different parts of the plant. The values used by GEMA-10L and the HMGU model are radionuclide dependent and are 0.09 for ^{79}Se, ^{129}I and ^{135}Cs and 0.005 for ^{226}Ra and ^{238}U. This significantly reduces the activity in the plant at consumption.

As noted above, the approach to calculating plant concentration by foliar interception is virtually identical in terms of the representation of the processes in GEMA-10L and the HMGU model. The results in Figure 16 are clearly different, in that GEMA-10L gives the same result for boreal and temperate conditions whereas the HMGU interpretation shows a progressive increase consistent with increasing radionuclide input in the irrigation source term of the warmer climates. In fact, the GEMA-10L and HMGU results for boreal and Mediterranean climates are close; the only major difference lies in the interpretation of the irrigation rate. HMGU assumes a constant irrigation rate during the period and GEMA-10L assume individual events. The amount of water involved in the adsorption into the plant tissues differs. There are 4 irrigation events in each of the temperate and boreal cases so that the same amount of activity enters the plant in each case for GEMA-10L. In the HMGU model there is no dependence on the number of irrigation events so that there is more activity in the temperate case than the boreal – and still more in the Mediterranean case with the increased irrigation requirement.

There is also an increased concentration in the plant in GEMA-10L because of the increased irrigation requirement but this arises because there are now 8 irrigation event rather than 4. It is possible to interpret the Mediterranean irrigation data so that there would be 16 irrigation events – effectively doubling the amount of activity adsorbed into the crop through the leaf surfaces and approaching the value seen in the more conservative SCK/CEN and CIEMAT models.

The explanation for this feature of GEMA-10L is that the leaves can hold only a limited fraction of the intercepted irrigation water [57]. If all irrigation really were to be applied in a single continuous stream the intercepted fraction would be quite low. However, irrigation is applied, as a matter of practicalities, as and when required and so multiple instances are the norm. Each event can retain and adsorb the same amount of activity – providing of course that the irrigation volume is sufficient to coat the leaves to the thickness specified in the S_p parameter of Equation (II.5).

This is a potentially important mechanism in increasing the radionuclide content of irrigated crops. As seen in the results for the boreal and temperate cases the approach taken by GEMA-10L and HMGU leads to lower concentrations than the more conservative models of SCK/CEN and CIEMAT, yet the inclusion of the irrigation-event-dependency produces results of similar magnitude to the more conservative interpretation. Note that there is no radionuclide dependency in the CIEMAT interception model. Both ^{226}Ra and ^{238}U have an implicit translocation factor of 1.0 in Equation (II.3) and, for each, the interception factor is assumed to be 0.5.

II.4.4. Foliar interception vs root uptake

Figure 17 shows the ratio of the concentration by foliar adsorption to root uptake for steady state conditions. For the compartment models, most of the radionuclides considered here and for the database assumed, root uptake is the dominating mechanism for incorporating radionuclides into plant via irrigation. Root uptake leads to concentration in the crop that are up to ten times higher.

^{129}I is the exception, however, foliar interception dominates but a factor 100 to 1000. The reason for this is the low k_d of ^{129}I in the sandy soil assumed for the case: 4.1×10^{-3} m^3 kg^{-1} compared to the next lowest, 5.6×10^{-2} m^3 kg^{-1} (^{79}Se). The high soil-plant transfer factor for ^{79}Se means that ^{238}U (low k_d and moderate soil-plant factor) has the next highest ratio.

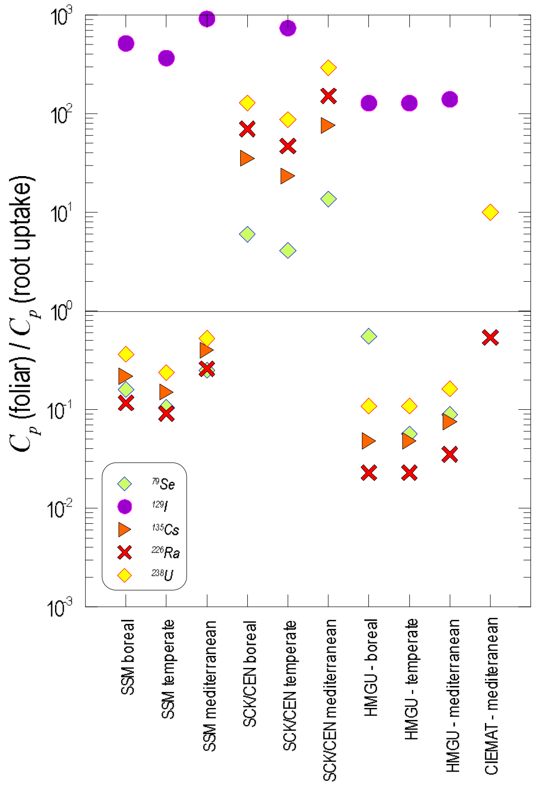


FIG. 17. Ratio of plant concentration by foliar adsorption to concentration by root uptake. Above 1, foliar adsorption dominates the content of the crop, below 1, root uptake dominates.

The low soil concentration calculated using HYDRUS mean that foliar adsorption is the dominating mechanism for all radionuclides using this interpretation. In the CIEMAT model, ^{238}U concentration in plants is similarly dominated by foliar adsorption because of the low soil concentration in Figure 14.

The situation described in the case evaluated here is somewhat artificial in that the intention was to make one set of site conditions, differentiated primarily by climate factors. This can be done but at the expense of rendering the models somewhat artificial. In the following section there are contributions from three of the participants which feature a greater degree of site detail relevant to the conditions in the different climate state analogues considered.

II.4.5. Additional contributions – site specific considerations

II.4.5.1. Local hydrogeology in Swedish boreal conditions

Hydrology in the irrigation example is relatively simple. Irrigation and precipitation, less evapotranspiration, combine to give an net annual downward flux that drains the area of farmland on which the crop is grown. Implicitly, there is no connection between the source of irrigation water and the infiltrating water. Such hydrologic regimes are common enough in regions of high relief although the possibility of the exfiltration of contaminated groundwater to the near surface environment is of interest in long-term waste disposal assessments, at least as a conceptual possibility. This section (describing aspects of Swedish conditions) and that following (Spanish conditions) discuss models with high water tables.

A key feature in the Swedish boreal landscape – such as that found around the planned site for a deep repository for spent fuel at Forsmark – is the general low relief with low topographic gradients. Combined with the shallowness of soils (mainly glacial tills) of a few metres thickness overlying the crystalline bedrock, the water table is often within a metre or less of the surface and the natural landscape comprises lakes, wetlands and forests. Release from the "geosphere" in this context means discharge from fractures to the lowest parts of the topography. Thus coastal bays, lakes and eventually wetlands are the landscape features likely to receive direct input of radionuclides from the bedrock. Isostatic landrise is also at work so that the coastline is rapidly retreating as the rebound from the previous glaciation amounts to 6 mm a^{-1} at Forsmark.

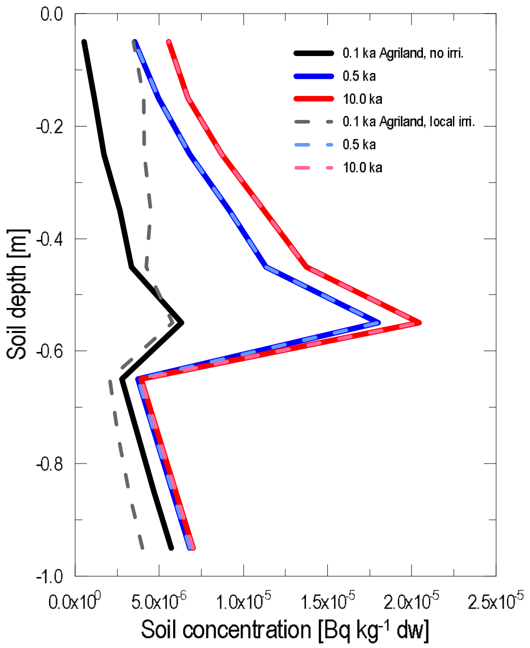
Under such conditions there is no necessity for an irrigation source term to bring radionuclides in groundwater from deep below the surface, there can be a contaminant bearing water flux upwards through the base of the sol column. Indeed, this is more likely than irrigation and conditions for the release may remain fairly constant over long time periods – enough to allow for the evolution of the lake-wetland system. A key interest, therefore, is the understanding of the accumulation of radionuclides in these natural features. Analysis of the scenario described for this working group has indicated that long timescales are required for significant accumulations of contaminants in soils. In the Swedish context the question is how large such accumulations can become.

Accumulation can occur in natural ecosystems (lakes, wetlands, forests) but it is with the transition of natural soils to agricultural land through the emplacement of a managed drainage system that is of primary concern. The question of prior accumulation is discussed [48]. Here the opportunity to discuss accumulation in agricultural systems is taken.

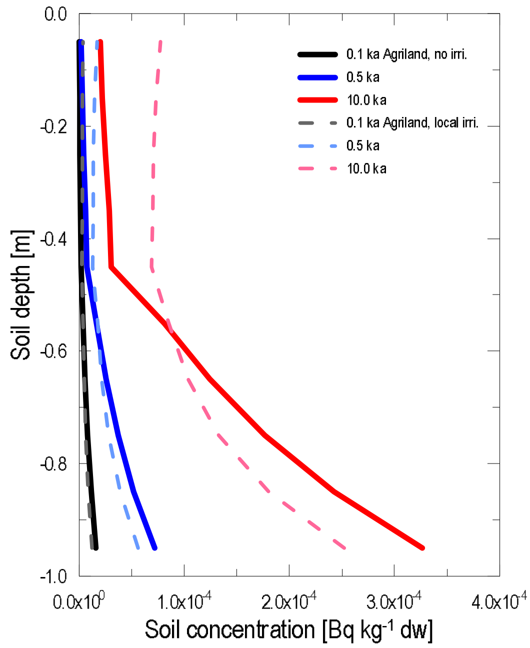
With the water table set to -0.5 m by the emplaced drainage system [67] there are different redox conditions in the 1 m soil column – oxidising in the upper 50 cm and reducing below. Two of the radionuclides in considered above have particular relevance in the Swedish context: ^{129}I and ^{226}Ra. The soil concentration is useful as an analogue for crop concentration by root uptake. ^{129}I is redox sensitive and a database has been published [71] for ^{129}I in Canadian peat bogs which shows a k_d dependence on oxidising conditions. For reducing conditions a value of $k_d = 4\times10^{-3}$ m^3 kg^{-1} is appropriate but above the water value is $k_d = 3\times10^{-2}$ m^3 kg^{-1}. In the variably saturated zone (from -0.6 to -0.3 m) the oxidising value is used with annually averaged values for the soil moisture content in the layers of the soil column.

Figure 18 shows the distributions of ^{129}I and ^{226}Ra in the 1 m soil column for alternative release assumptions:

- Release from the fracture network to the base of the soil column at a rate of 1 Bq a^{-1}, no irrigation,
- Release from the fracture network to the base of the soil column at a rate of 1 Bq a^{-1}, combined with irrigation from the local source (saturated zone) – 4 events of 0.025 m^3 m^{-2} per event,



(a) ^{129}I



(b) ^{226}Ra

FIG. 18. Profiles of ^{129}I and ^{226}Ra at three different times for alternative release scenarios for boreal conditions, managed drainage, with water table at -0.5 m. Continuous lines denote upward migration following release to bottom of the 1 m soil column of 1 Bq a^{-1}. The thicker, dashed lines denote the effects of irrigation from the subsurface aquifer (with recirculation of infiltrating water) for the same release.

In Figure 18 (a) the results for ^{129}I show chemical zonation as a result of differences in the redox conditions in the profile. There is the characteristic profile of accumulation at the interface between the saturated and unsaturated layers as reported in field experiments [72]. Because of the mobility of iodine with the assumed k_ds, the results come rapidly into equilibrium so that by 500 years the profile is identical. Irrigation leads to higher concentrations in the upper soil layers at early times (illustrated at 100 years here) but the accumulations in the top soil by direct irrigation soon leach to the steady-state distribution.

This result means that accumulation by upward migration is just as effective at contaminated the upper soil as irrigation and this is as a result for zonation in the system with the higher k_d in the oxidising layers leading to a redox barrier developing. In the results for the EMRAS calculations ^{129}I concentrations in crops is dominated by irrigation interception. However, the default soil-plant transfer factor used in Swedish assessments comes from a compilation [73] and is substantially higher that the value employed above. With such variability natural accumulations by upward migration could easily come to dominate the dose from ^{129}I, the key being relative mobility in the saturated zone and relative *im*mobility in the better quality agricultural soils above the local drainage system.

It should also be remembered that, for comparison purposes, a lower concentration is to be expected in lake water that would be found in the porewater of the saturated soil layers. It is therefore unlikely irrigation from a lake would led to such a high input rate compared to the upper soil to that arising from local aquifer sourced activity. Equally importantly, the accumulation in the non-irrigated case here could arise where a chronic release from the fracture to the base of the soil occurred. Such a release is more likely than the assumption of continuous irrigation of 10 ka used to illustrate the accumulation process.

In contrast the results for ^{226}Ra have no redox sensitivity. Upward migration in the soil column is limited by the high k_d (3.1 m^3 kg^{-1}) and there is a build-up at depth which falls rapidly to the level of the drain at -0.5 m. Bioturbation is important in the unsaturated zone in distributing activity higher up the column. In this case irrigation from the external, constant concentration source would produce similar concentrations in the upper soil to that found at depth in the non-irrigated case, were chronic irrigation to be implemented. Irrigation from the local aquifer source is less effective that the external source but more so than the non-irrigation case.

As modelled here, there is no removal of the upper layers of soil by erosion and other processes. Over the long term, say 10 ka, this assumption may not be reasonable. There is scope for the significant accumulations at depth to "migrate" to the surface layer of soil. In drier conditions in the future, caused by climate change, it is reasonable to assume that the upper soil layers might be readily removed by wind erosion. Significant concentration in the upper soil layers can then be envisaged without the need to assume long-term irrigation at the same site.

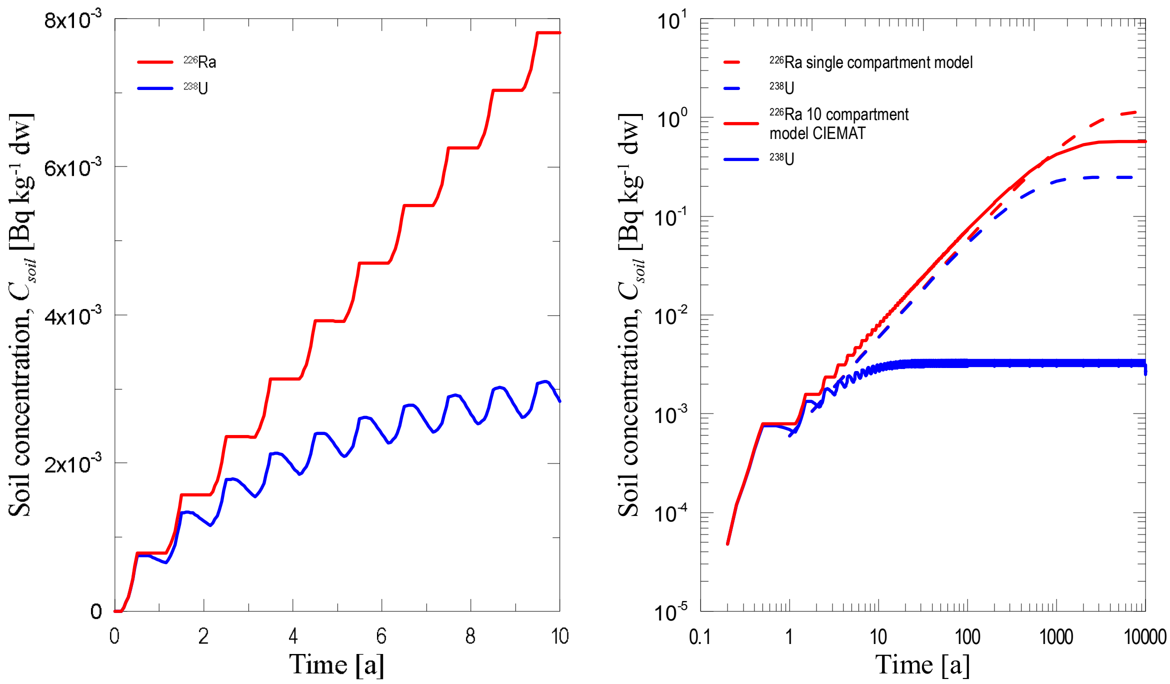
These considerations illustrate that there are more FEPs that need to be incorporated in the assessment model than those of climate change and that they should be integrated into to the full assessment modelling tool such as a much shallower water table in the landscape is clearly demonstrated for Swedish conditions.

II.4.5.2. Variable water table in near-surface soils in Spain

It is not only in Scandinavia that near-surface water tables are of concern. The model employed here by CIEMAT has been specifically developed to address the problem and to evaluate redox sensitivities of selenium [51]. The model has been revised to allow results for ^{238}U and ^{226}Ra (including daughters) to be calculated. This is the basis for the calculation for uranium and radium included in the results in the preceding section.

The model is of interest because it is a multi-layer compartment model that makes use of monthly water balance figures. CIEMAT use these details to simulate the movement of the water table height and thereby to generate the water fluxes between and moisture content in 10 equispaced soil layers as a function of time during each year. These fluxes are then used to drive radionuclides transport for ^{238}U and ^{226}Ra (with daughters).

Figure 19 provides a closer look at the results from the model. To the left, the top soil concentration as a function of time is shown for the first 10 years from the commencement of irrigation. With its lower k_d, the interannual variation for ^{238}U shows a series of peaks and troughs on an increasing trend with steady state established over a period of around 10 years. For the more strongly sorbing ^{226}Ra there is an increase during the irrigation period, as with the uranium, but the accumulated material is unaffected by varying water fluxes in the soil because of the high sorption. Concentration of ^{226}Ra stays constant during this period. For the less strongly sorbed uranium there is a loss during this period.



(a) Interannual variation in the concentration of the top 0.1 m of soil as a results of fluctuating water table for the first 10 years after the start of irrigation.

(b) Long term accumulation in the upper soil over a period of 10 ka.

FIG. 19. Comparison of the results from the CIEMAT model with variable water table height and those for a single compartment model.

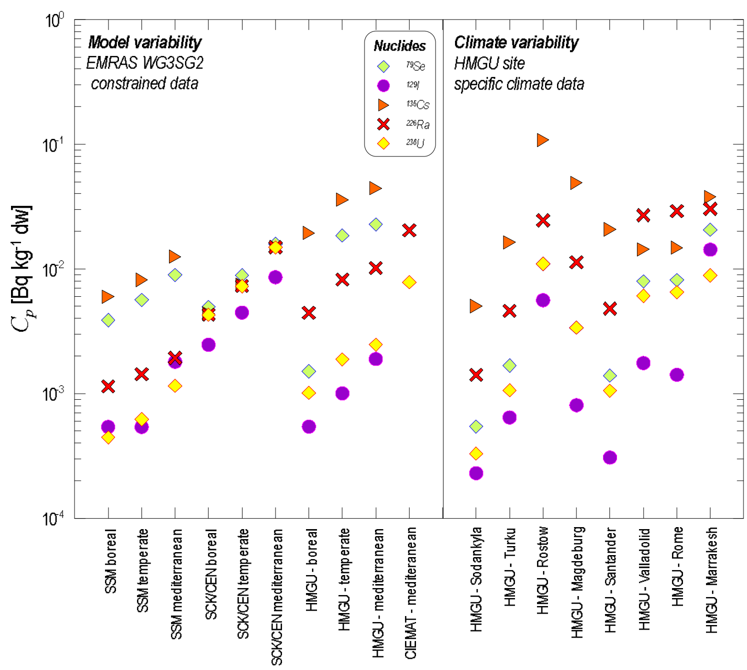


FIG. 20. Results for total activity concentration in plant for the three climate states identified in this exercise, as contributed by the participants, compared to the results from HMGU and their analogue climate states as evaluated as part of Subgroup 1's activities.

Compared to the results for a simple one-compartment model the radium behaves in a fairly straightforward way on the long-term, the high k_d dominating over the variability caused by the fluctuating water table depth. The results show accumulation to similar levels in the upper soil. The single compartment results are higher but this can be accounted for by the distribution in the remainder of the 10 layer column.

The effect of the variable water table appears to be enhanced leaching of low k_d-species (the uranium here). The long-term equilibrium value for ^{238}U in the CIEMAT model is around one and a half orders of magnitude lower than the simple interpretation of the case. Here the interannual variation is more pronounced, though not easily represented on the log-axis.

II.4.5.3. Conceptual model uncertainty and variability in analogue climates

This working group has concerned itself with the way in which key soil-plant processes are represented in models for long-timescale waste disposal assessments. There are 4 participating organizations with different models and interpretations of the system to be modelled. Three climate states are considered and in characterising them the focus has been on the *climate distinctions between them*. As modelled in the exercise, therefore, the differences are restricted to the conceptual representation of the soil-plant FEPs include in the models used.

During the initial phase of the calculations, the HMGU group contributed a set of results obtained in the context of the modelling of climate analogues in SG1. Figure 20 shows the results for total plant concentration (root uptake + foliar interception) for the 3 sites described in this exercise and these are compared to the overall variation for the 8 climate stations described in SG1.

The results indicate that there remains some residual variability in the "real world" that is not expressed in the modelling of the soil-plant system but this amounts to only around an order of magnitude. The extremes are for extreme cold conditions (Sodankyla) – which are not well represented in the database used here, and the warm and wet Rostov. Overall, climate variability leads to around one and half orders of magnitude variation in plant concentration using traditional modelling.

II.5. CONCLUSIONS AND RECOMMENDATIONS

SG2 has investigated the impact of climate factors on a key part of the biosphere – the mechanisms relating to the incorporation of radionuclides into crops. Specifically, the source is irrigation with foliar adsorption and root uptake giving rise to accumulation in agricultural crops. Four groups contributed results addressing the central theme of the exercise (modelling the effects of climate change) to be met but also providing additional material that allowed a discussion of accumulation processes due to the effects of local hydrology and corresponding redox conditions, the spatial and temporal discretisation of the model system to be addressed and a comparison of model variability versus climate variability to be made.

Participating models included simple and more complex compartment structures, static and variable water table height and two models which solve the full Richard's equation using time series for hydrologic input on a daily basis. The compartment models generally employed annual averaging of climate and other parameters.

Boreal, temperate and Mediterranean climate conditions were selected and data provided by participants for site in their own national programmes which fitted the requirements of the exercise. Crop and soil conditions were assumed to be the same in each site so that the focus in the modelling would be on the treatment of climate factors. Calculations of soil concentration as a function of time and crop concentration by the two parallel mechanisms of foliar adsorption of contaminated irrigation water and root uptake from contaminated soil were selected as endpoints.

The exercise reported here shows that the even using the same basic site description the results differ according to the models used. There is an apparent difference in the participating models between the simple model and the more complex model interpretations. This suggests that model uncertainties can be usefully explored in a dose assessment by using alternative models.

Furthermore, the uncertainty identified here, whether due to model or parameter uncertainty (each giving a range of around two orders of magnitude in Figure 20), should be propagated through to the dose calculations. The impact must be addressed either qualitatively or quantitatively through a validation of models and parameters.

Biosphere dose assessment models are abstracted from FEPs. A thorough review of all relevant FEPs is essential for developing assessment models for specific sites. This is emphasised here by the variation in interpretation of irrigation in the participating models (Figures 16 and 17). Further review of the treatment of irrigation in long-timescale assessment models would be beneficial.

Irrigation remains the most straightforward way of getting activity concentration in agricultural crops. For higher k_d nuclides the time taken to accumulate in soil is often longer than the timescale for chronic cultivation scenarios. However, results for geochemical zonation at the saturated/unsaturated zone boundary, seen in the results from GEMA-10L (Figure 18), also indicate the need for to review the FEPs associated with accumulation. For a release to the base of shallow soils, it is possible, depending on the radionuclide’s k_d, to obtain concentrations in the rooting zone of soils that are close to those arising from direct irrigation scenarios.

Because a fundamental assumption behind compartmental models is instantaneous mixing of solute in each compartment, the spatial distribution of contaminants in the system may not always well represented to the degree relevant to the assessment objectives. Therefore, the effect of model discretisation on modelling results should be analysed [74, 75]. There are indications that the use of temporal scales less than annual averaging might lead to differences in soil concentration (Figure 14). This use of interannual data should be pursued, particularly when used in conjunction with a dynamic plant sub-model and a variable water table height, as discussed above.

One of the participating models employed a dynamic plant as part of the soil-plant system. Results were somewhat different and the reasons should be investigated, particularly as this model also employed a dynamic water table height.

APPENDIX III. APPLICATION OF DYNAMIC TREATMENT AT A SPECIFIC SITE

The following sections illustrate how site specific dynamic consideration of environmental change can be implemented based on the Forsmark site in Sweden. The site descriptive texts below rely heavely on, and cite work done within the SKB safety assessment SR-Site[8].

III.1. SYSTEM DESCRIPTION

The Forsmark area is located at the shoreline of the Baltic Sea in northern Uppland, Sweden. Post-glacial land uplift, in combination with the flat topography, implies fast shoreline displacement that has resulted in a very young terrestrial system that contains a number of newborn shallow lakes and wetlands. See Figure 21 The lakes themselves are also of a specific type that is only found in northern Uppland. Shallow and with sediments rich in calcium, the lakes are unique in Sweden. Hydrologically, the area also differs from the regional pattern. High water flows in the upper part of the bedrock are associated with a complex network of gently dipping and sub-horizontal, open and partly open fractures in the upper part of the bedrock.

The latest deglaciation in Forsmark took place during the Preboreal climatic stage, c. 10 800 years ago. Forsmark is situated below the highest coastline, and when the latest deglaciation took place, the area was covered by c. 150 m of water. The closest shore/land area at that time was situated c. 80 km to the west of Forsmark. The shoreline displacement has strongly affected landscape development, and still causes a continuous and relatively predictable change in the abiotic and biotic environment, e.g. in water and nutrient availability. The first parts of Forsmark emerged from the sea around 500 BC. Thus, the post-glacial development of the surface system is determined mainly by the development of the Baltic basin and by the shoreline displacement [76].

The study area is characterized by a small-scale topography with limited variations in altitude and is almost entirely located less than 20 m above sea level. Till is the dominant Quaternary deposit (QD), whereas granite is the dominant rock type. The annual precipitation and runoff are 560 and 150 mm, respectively [77]. The lakes are small (the largest lake is around 0.6 km^2) and shallow, with mean and maximum depths ranging from approximately 0.1–1 m and 0.4–2 m, respectively. Sea water flows into the most low-lying lakes during events with very high sea levels. Wetlands are frequent and cover 25–35% of some of the delineated sub-catchments.

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[8] As well as the references cited in the text, the reader is also refered to the following references which provide a thorough synthesis of understanding of the Forsmark site and analysis of its future landscape development. Work in contribution to these references was used in support of the preparation of the WG3 report, but the references themselves were not published at the time the particular WG3 work was completed, and so were not included in the reference list.

— LINDBORG, T. (ed), Landscape Forsmark – data, methodology and results for SR-Site. SKB TR-10-05, Svensk Kärnbränslehantering AB (2010).
— LINDBORG, T., BRYDSTEN, L.,, NÄSLUND, J-O., KAUTSKY, U., Landscape development in the safety assessment of a potential repository in Forsmark, Sweden. Radioprotection, vol. 46, n◦ 6 (2011) S639–S645. DOI: 10.1051/radiopro/20116656s
— KAUTSKY, U., LINDBORG T., AND VALENTIN, J., (ed.). Humans and Ecosystems Over the Coming Millennia: A Biosphere Assessment of Radioactive Waste Disposal in Sweden. AMBIO 42 (4): 381–526. (2013).

FIG. 21. Photograph from Forsmark showing the flat topography and the low gradient.

No major water courses flow through the central part of the site investigation area. The brooks downstream of Lake Gunnarsboträsket, Lake Eckarfjärden and Lake Gällsboträsket carry water most of the year, but can be dry for long periods during dry years such as 2003 and 2006. Many brooks in the area have been deepened for considerable distances for drainage purposes.

The horizontal hydraulic conductivity and specific yield of the till are, based on measurements, considered typical or slightly higher than in the surrounding region. Groundwater levels in QD are very shallow, on average less than 0.7 m below ground during 50% of the time. Shallow groundwater levels imply a strong interaction between evapotranspiration, soil moisture and groundwater. Diurnal fluctuations of the groundwater levels, driven by evapotranspiration cycles, are evident in many groundwater wells. Furthermore, groundwater level measurements in the vicinity of the lakes show that the lakes may act as recharge sources to till aquifers in the riparian zone during summer.

There is a close correlation between the topography and the groundwater levels in the regolith. For groundwater levels in the upper bedrock there is no such strong coupling to the topography. This is most evident in the central part of the study area, where the groundwater-level gradients in the bedrock are very small, indicating a high transmissivity. Here, the groundwater levels in the till in general are considerably higher than in the bedrock. The result is that local, small-scale recharge and discharge areas, involving groundwater flow systems restricted to the regolith, overlie the more large-scale flow systems associated with groundwater flow in the bedrock.

The flow systems around and below the lakes are quite complex. The lake water/groundwater level relationship, under natural as well as disturbed conditions, indicates that the lake sediments and the underlying till have low vertical hydraulic conductivities. The groundwater below the lakes often has relict marine chemical signatures, whereas the groundwater in the riparian zone is fresh.

The surface water and shallow groundwater in Forsmark are characterized by high pH-values and high concentrations of major constituents, especially calcium and bicarbonate [78, 79]. The main reason for this is the glacial remnants, mostly in the form of a till layer, that were deposited during the Weichselian glaciation and deglaciation [80]. This till layer has a rich content of calcite, originating from the sedimentary bedrock of Gävlebukten about 100 km north of Forsmark.

The marine ecosystem at Forsmark is situated in a relatively productive coastal area in a region of otherwise fairly low primary production. The surface water has nutrient concentrations ranging from 330–790 µg L^{-1} tot-N and 12–25 L^{-1} tot-P. The seabed is dominated by erosion and transport bottoms with heterogeneous and mobile sediments consisting mainly of sand and gravel with varying fractions of glacial clay. The seabed close to the mainland has some areas of rocky bottoms, which are partly covered by coarse till.

The characteristics of the limnic ecosystem in the Forsmark regional model area are to great extent determined by the small topographic gradients in combination with the ongoing shore displacement and short distance to the sea, and by the occurrence of calcium-rich deposits. The lakes are classified as oligotrophic hardwater lakes, i.e. they contain high calcium levels, but low levels of nutrients, as phosphorus is precipitated together with calcium. Due to the shallow depths, the theoretical water retention times of the lakes are generally shorter than 1 year.

The terrestrial vegetation is affected by the bedrock, the nature of the QD and human land use. The QD are mainly wave-washed till, where conifer forests are common. In depressions, a deeper regolith layer is found, with fairly high lime content. The calcareous influence is typical for the north eastern part of Uppland County and is manifested in the flora. A major part of the wetlands are coniferous forest swamps and open mires. Arable land, pastures and clear-cuts dominate the open land. Arable land and pastures are found close to settlements. The pastures were earlier intensively used, but are today a part of the abandoned farmland following the nation-wide general regression of agricultural activities.

III.2. PROCESSES AND PARAMETERS POTENTIALLY AFFECTED BY ENVIRONMENTAL CHANGE

During a typical glacial cycle Forsmark will exhibit a temperate climate domain during the initial 25 000 years, even though this domain will be interrupted with shorter periglacial climate domains. During a temperate climate domain, the spatial distribution of ecosystems in the area will change due to the shoreline displacement, decreasing the initial extensive marine area (the submerged marine stage, in average a 150–200 m deep offshore area) and extending the areas for limnic and terrestrial ecosystems as a result of the regressive shoreline.

In the present landscape of Forsmark the shoreline displacement has over long periods continuously created inshore bays, lakes and new land areas. The subsequent succession of these emerging areas follows different trajectories depending on local factors such as wave exposure during the marine shore stage, slope and surrounding topography. Succession is a directional change of ecosystem structure and functioning, which may occur over time scales from decades to millennia.

III.2.1. Marine environments

Sheltered marine areas and bays accumulate organic and fine-grained inorganic material, whereas the finer fractions are washed out from more wave-exposed shorelines with a large fetch. The shoreline displacement will bring marine basins initially located far out in the open sea, adjacent to the shore, thus increasing the effect of runoff from land, which may influence water chemistry, nutrient load and light penetration. As the area become shallower and more secluded, the water turnover will become slower. The marine ecosystem part of the model area in Forsmark decreases due to the shoreline displacement and around 11 500 AD only limnic and terrestrial ecosystems exist in the area.

Future temperate marine ecosystems will be similar to those at present. Nevertheless, the predicted abiotic changes will alter the size of functional groups and the magnitude of the fluxes within the ecosystem. The major change will be when an ecosystem in a deeper offshore area shifts from being dominated by pelagic primary producers to benthic primary producers, along with the uplifting of the sea-floor. However, the primary production in these shifting habitats will still be of similar magnitude to that in the presently existing shallower coastal areas. At present, the whole marine area in Forsmark is net autotrophic, due to the high primary production in the shallow areas and in the long term future it is likely that the marine ecosystem will continue to be net autotrophic.

The influence of less saline discharge water from land will lower the salinity and the organisms will shift from being a mix of freshwater and saline species in the Baltic Sea, towards a dominance of more freshwater species. Around 11 000 AD, when the marine area in Forsmark is almost completely gone from the model area, the salinity will have decreased to between 2–3 ppm, which is consistent with present Bothnian Bay conditions. The Bothnian Sea will be isolated from the Baltic Proper around 25 000 AD and become a large freshwater lake.

III.2.2. Limnic environments

A sea bay may both be isolated from the sea at an early stage and thereafter gradually turn into a lake as the water becomes fresh, or it may remain as a bay until shoreline displacement turns it into a wetland. After isolation from the sea, the lake ecosystem gradually matures in an ontogenetic process which includes subsequent sedimentation and deposition of substances originating from the surrounding catchment or being produced within the lake. Hence, the long-term ultimate fate for most lakes is an inevitable fill-up and conversion to a wetland.

In Forsmark, all present day lakes have developed into shallow oligotrophic hardwater lakes that are characteristic of the area. In the future, shoreline transgression will isolate deeper marine basins and turn them into freshwater bodies. These deeper lakes can be expected to differ somewhat from the shallow oligotrophic lakes of today. In addition, some of the shallow lakes that will form may turn into dystrophic brown-water lakes. Three of the future lakes will have depths of more than 10 m and these are considered to represent deep lakes. The remaining lakes that form will have depths around 2 m or less and are considered shallow. Below follows a brief description of the expected functioning of future shallow and deep lakes, and streams in the Forsmark area.

Many of the shallow lakes that will emerge due to land-rise are assumed to closely resemble the present-day oligotrophic hardwater lakes in Forsmark with high primary production on the lake floor. However, it is also possible that they will become dystrophic, i.e. with brown water and dominated by respiration of allochthonous material produced in the surrounding terrestrial catchment. The development of brown-water systems is coupled to the retention time and character of upstream lakes [81]. Present lakes that have emerged in the catchments of Forsmark-Olandsån have evolved into dystrophic lakes, mainly due to the inflow of brown water from upstream dystrophic lakes.

In contrast, emerging lakes without large input of brown water are likely to become oligotrophic hardwater lakes. In addition, one could hypothesise that lakes with short retention times should be dystrophic due to turbidity of the water. However, many of the present-day Forsmark lakes have short retention times so it is evident that lakes with short retention times may also become oligotrophic hardwater lakes. The retention time in future lakes spans a wide range but the majority of the shallow lakes in the future are assumed to become oligotrophic hardwater lakes [82].

The future oligotrophic hardwater lakes are assumed to be similar to the present lakes in the area and most of them are modelled to be net autotrophic. However, immediately upon isolation some of the shallow lakes may be dominated by respiration. Respiration decreases as the lakes become shallower (due to sediment accumulation) and the proportion of photic area increases in the lakes, i.e. with time these lakes also turn autotrophic. On the contrary, if the emerging lakes are dystrophic it is likely that they remain heterotrophic for their entire lake stage.

The deep lakes that will emerge in the Forsmark area differ from the shallow ones in a number of respects and are assumed to more closely resemble other deep lakes in the county. The greater depths of the future lakes result in aphotic areas where benthic photosynthesis does not occur, whereas respiration does occur. This together with a short retention time and thereby large inflow of allochthonous material indicates that the lakes will become net heterotrophic. The lakes will be deep enough to allow for thermal stratification during summer and/or winter. During stratification no mixing of deeper and shallower water occurs and anoxic conditions in the deeper water may release nutrients from the sediment leading to high nutrient concentrations. Higher nutrient concentrations and areas with low light climate indicate that primary production in the pelagic habitat may be much higher in the deep lakes than in the shallow lakes whereas benthic primary production is likely lower.

In the future deep lakes, a large part of pelagic production may be utilized directly in the pelagic habitat by zooplankton, but the losses through the outlet are probably large due to a short retention time. There will most likely be higher habitat diversity in larger than smaller lakes considering both vegetation and animals. For example, is it likely that the future deep lakes will contain more fish species. Biomasses per hectare, on the other hand, are most probably similar to those in the present oligotrophic hardwater lakes.

In the future, larger streams than those currently present will be formed in the area, and are assumed to more closely resemble the River Forsmarksån. These deeper streams are assumed to not host benthic primary producers, but on the other hand, they may contain larger amounts of pelagic producers. The retention time in future streams will be shorter than at present, due to larger water flows, induced by larger drainage areas. This larger flow indicates that these larger streams will also function as transport routes as there will most probably be insignificant sediment accumulation.

III.2.3. Terrestrial environments

Mires are formed basically through three different processes: terrestrialisation, paludification and primary mire formation. Terrestrialisation is the filling-in of shallow lakes by sedimentation and establishment of vegetation. Paludification, which is the dominant process of mire formation in Sweden, is an ongoing water logging of more or less water-permeable soils, mainly by expanding mires. Primary mire formation is when peat is developed directly on fresh soils after emergence from water or ice. All three processes are likely to occur in the Forsmark area, but terrestrialisation probably represents the largest areas of peatland development in the investigation area today.

This pattern, where reed is the dominating pioneer during terrestrialisation, is also seen in the peat archives of bogs further inland [83, 84], although the extent of the historical importance of reed during terrestrilisation is uncertain. Other important stages in peatland development are dominated by sedges (*Carex*) and/or brown mosses (*Bryales*) and *Sphagnum*, respectively. Forested wetlands are found in different stages of the wetland ontogeny, where wood-*Carex* peat (Birch and/or Alder) often is found earlier in the succession and wood-*Sphagnum* peat (Scots pine) may be a part of the last successional stage.

The richer types of mires, which are typical of the Forsmark area, will undergo a natural long term acidification when turning into more bog-like mires. Most wetlands are discharge areas; however, the raised bog, with rain-fed production on the bog plane has a restricted or nonexistent connection to the groundwater table, and is of less interest in a safety assessment where the radionuclides enter the ecosystem from below. Moreover, the potential yield after drainage will decrease drastically if *Sphagnum* peat dominates the surface layers (i.e. a bog) and other wetlands would be preferred for agricultural purposes.

The largest part of the land area is, however, not defined by the stages described above and is dominated by till and outcrops. The Baltic Sea shore can be divided into 4 different types: rocky shores, shores with wave-washed till, sandy shores and shores with fine sediments. Wave-exposed shores will undergo a relocation of previously accumulated sediments, and these shores will emerge as wave-washed till, where the grain size of the remaining sediments is a function of the fetch at the specific shore. Shores with wave-washed till are the most common kinds in the Forsmark area, but rocky shores and shores with fine sediments can also be found.

The emerging rocky and till shores have a sea shore vegetation zonation that is defined by their tolerance to water inundation and salt sprays. Bushes and trees create a varied light environment and new habitats. In this way, the flora and vegetation change steadily but with a relatively high degree of determinism. In most areas with a thicker soil layer, Norway spruce forest has to be regarded as the dominating vegetation type in this area, if the management and land-use were to decrease. Scots pine would probably be more restricted to areas with a shallower, more nutrient poor soil layer if forestry management was to decrease and fire was once again to become a natural disturbance in the landscape.

Figures 22 and 23 illustrate processes and parameters potentially affected by environmental change and warmer climates. The figures show responses on couplings between ecosystem entities due to climate change. Table 42 provides examples of abiotic and biotic parameters describing the biosphere system which can be affected by climate change.

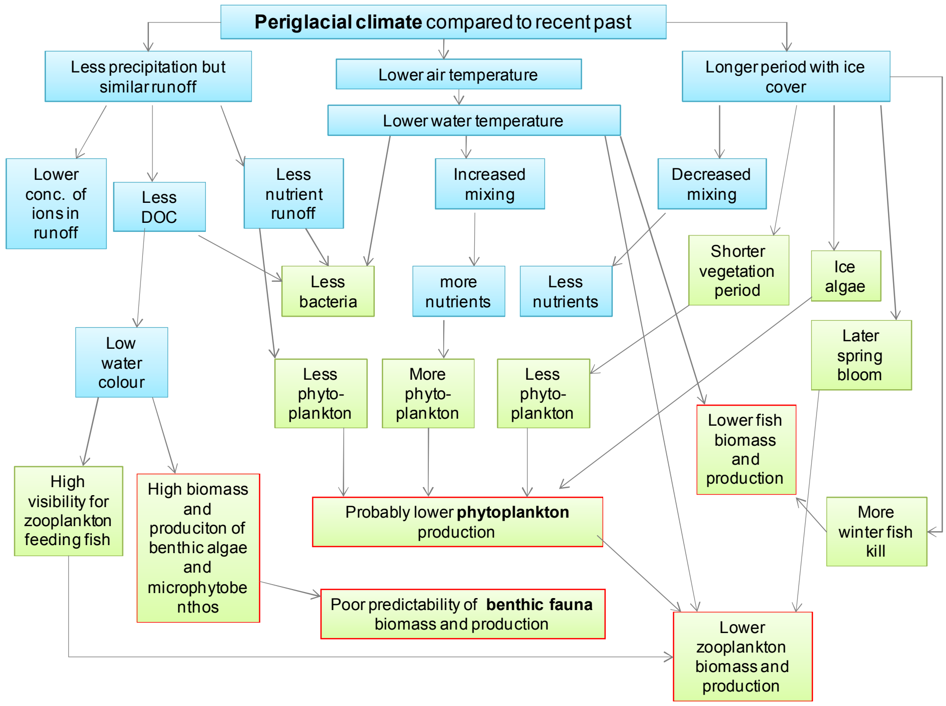

FIG. 22. Identified[9] changes in biotic processes and parameters due to colder climate.

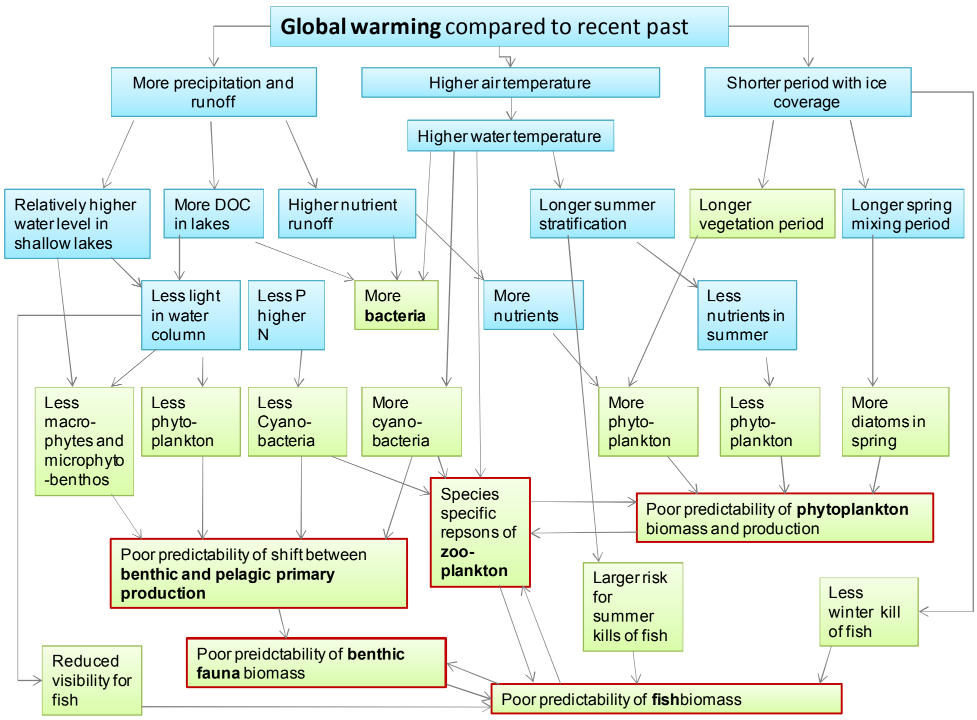

FIG. 23. Identified [8]changes in biotic processes and parameters due to warmer or extended temperate climate.

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[9] NOTE: Blue colour indicates abiotic and green biotic responses. The red frame shows the biotic functional groups handled in this study.

TABLE 42. IDENTIFIED ABIOTIC AND BIOTIC PARAMETERS AFFECTED BY CLIMATE CHANGE

Parameter: Abiotic	**Temperate Forsmark today**	**Global warming Bothnian Sea/Baltic proper**	**Periglacial**	**Glacial**
Period with ice coverage (days)	1–4 months	1-2 months shorter or absent	9–10 months	365
Total nitrogen concentration (mg L^{-1})	0.5 (0.2–2.8)	Probably higher	Probably lower	lower
Total phosphorus concentrations (mg L^{-1})	0.02 (0.007–0.06)	Probably higher	Probably lower	lower
DOC concentrations(mg L^{-1})	5 (1–21)	Similar to present, higher or lower	Probably lower	Lower
DIC concentrations (mg L^{-1})	11 (0.3–27)	Similar to present, higher or lower	Probably lower	Lower
Particulate matter (kg dw/m3)	0.4 (0.08–2.2)	Similar to present or higher	Probably lower	Lower
Oxygen free bottoms		more	~present	–
Salinity (‰)	4.4 (0.2–5.4)	<present / 0-15	<present / 0–15	–
Light penetration (m)	2.7 (0.3–6.4)			
Biotic parameters	Temperate	Global warming	Periglacial	Glacial
Phytoplankton biomass (g C m^{-3})	0.2 (0.02–0.5)	Similar to present, higher or lower	Similar to present, higher or lower	Lower
Chlorophyll (ug L^{-1})	1–4			
Microphytobenthos biomass (g C m^{-2})	2 (0.5–5)	Similar to present, higher or lower	Similar to present or lower	Lower

III.3. MODEL REPRESENTATION OF IDENTIFIED PROCESSES

Based on system description and understanding of climate change processes, an interaction matrix can be used help develop a model of how processes in the biosphere respond to environmental change, as illustrated in simplified form in Figure 24. Processes linking features in the leading diagonal elements are identified in the off-diagonal elements in a clock-wise manner.

Environmental change affects not only the biosphere and the changes need to be taken into account coherently within an assessment. Figure 25 illustrates an assessment flow chart - linking the models together. Note that the near field (NF) and far field (FF) part is greatly simplified here.

Formulated climate scenarios are fed into the development of the biosphere, especially the sea level change, but could also be other key climatic drivers like precipitation and temperature, and hence the water balance. These scenarios can be based on dynamic climate modelling and downscaling, too e.g. BIOCLIM output, Posiva's example of WR 2011-01 [85].

The biosphere is modelled taking into account land uplift, formation and overgrowth of lakes and suitability for agriculture. Depending on sites, it could include other processes, e.g. erosion in mountainous areas.

Water composition	(a) Phase transitions (b) Relocation (c) Resuspension	(a) Change of pressure (b) Light related processes (c) Reactions	(a) Phase transitions (b) Sorption/desorption
(a) Deposition (b) Phase transitions (c) Wind stress	**Gas and local atmosphere**	(a) Change of pressure (b) Convection (c) Heat storage (d) Phase transitions (e) Light related processes (f) Reactions	(a) Convection (b) Sorption/desorption
(a) Convection (b) Physical properties change (c) Reactions	(a) Change of pressure (b) Convection (c) Phase transitions	**Temperature**	(a) Reactions (b) Phase transitions
(a) Decay (b) Radiolysis (c) Reactions	(a) Phase transitions	(a) Decay	**Radionuclides**

FIG. 24. Example of interaction matrix (sub set) used in the analysis of environmental change, where grey indicates the leading diagonal elements, orange is of importance for safety assessments, blue is of importance and affected by climate change. The events and processes suggesting interactions between the features in the leading diagonal elements are suggested by the content the off diagonal elements.

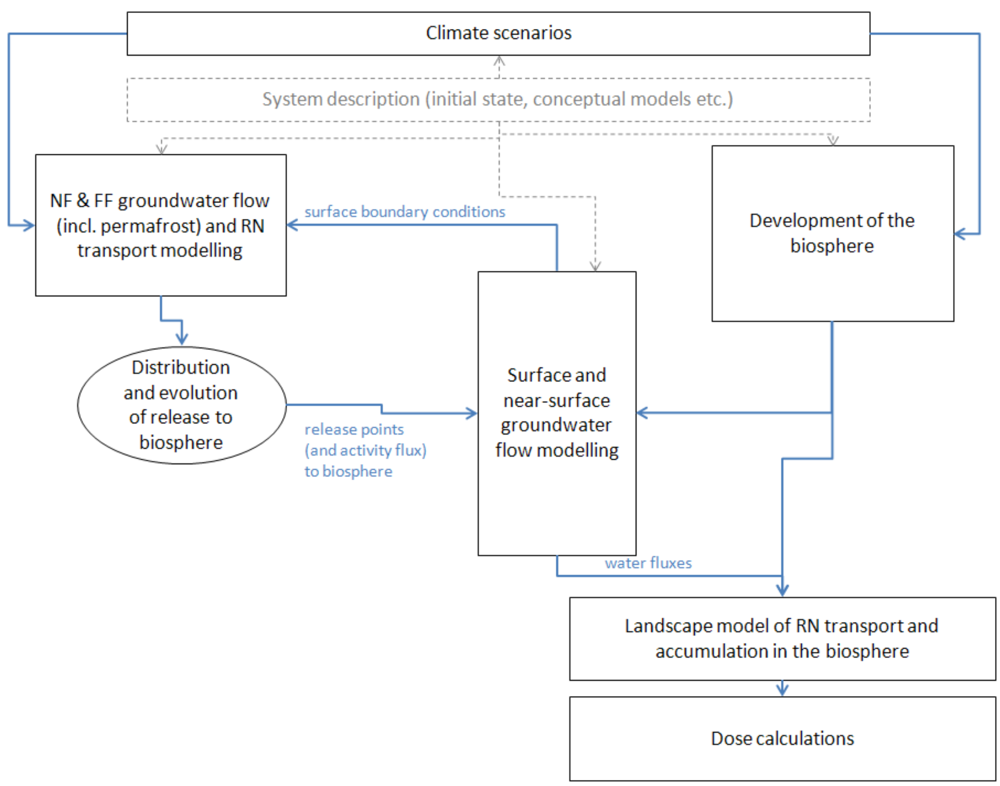

FIG. 25. Assessment flow chart – linking the models together.

These biosphere simulation results are used to feed into the surface and near-surface groundwater flow modelling such as that used to simulate the water balance and surficial groundwater flow [86]. This gives a boundary condition (e.g. groundwater pressure head at top of bedrock) to the deep groundwater flow modelling, which is further used for radionuclide transport modelling in the NF and FF. Using this kind of modelling is important, in order to get the water balance and fluxes correct and consistent with the other assumptions and models [87].

From the geosphere part of the model (or FF), release points and activity fluxes to the biosphere (in space and in time, m^3/y and Bq/y) are provided back to the surface and near-surface groundwater flow modelling which then refines the flow paths near the biosphere and where more accurately the releases go into in the biosphere radionuclide transport model. This phase could also take sorption in soils and sediments into account.

The biosphere-refined release points and the biosphere development modelling results are used to compile a radionuclide transport model (called here, a landscape model) which takes into account the source term (to the biosphere), the development of the biosphere, and the contaminated area downstream.

The results of the landscape model (activity concentrations) are used to derive doses and other endpoints to the specified exposure groups/populations, dynamically taking into account the climate change, the evolution of the biosphere system (e.g. drying mire into agricultural land) and a changes in use of land. Since the landscape is changing, characterization of a location assessed as potentially being an area to receive a radionuclide release from the geosphere, could be thought not so useful. To address this problem, analogue systems can be used which have already seen the change anticipated at the location in question. A for selection of real-life analogues for future lakes and mires at a repository site are available [88].

Table 43 provides examples of the changes in parameters in the model for radionuclide movement in the biosphere linked to change from temperate to permafrost conditions.

Table 44 provides examples of how productivity of foodstuffs in different ecosystem types (data used in the Posiva 2009 assessment [17, 89, 90] and the respective area needed to produce the annual amount of foodstuff required by a person annually consuming 110 kg carbon (for the adult male “Reference Man” [91, 92], and conversely, the number of people for whom 1 hectare could produce the adequate amount of food of each type.

TABLE 43. EXAMPLE INPUT DATA FOR RADIONUCLIDE MODEL SIMULATIONS FOR DIFFERENT CLIMATE CONDITIONS

Parameter	Temperate	Permafrost	% change	Unit
Atmosphere				
The concentration of carbon in the atmosphere	0.00020	0.00011	-48.0%	kg/m^3
Hydrology				
The total runoff in the model area	0.19	0.22	16.7%	m/y
Advective flux in the aquatic object between the sediment and the water during lake stage[a]	0.64	0.03	-95.0%	unitless
The fraction of the advective flux from the till that goes to deposits under the wetland	0.98	0.33	-66.3%	unitless
The total advective flux from till to glacial and post glacial after the marine phase	0.044	0.0030	-93.2%	m/y
The advective flux from post glacial and glacial deposits to Peat[a]	0.31	0.0014	-99.5%	unitless
The gross flux from wetland to lake[a]	1.3	1.1	-15.4%	unitless
Wet-land ecosystem				
The terrestrial biomass of primary producers	6,0	0.82	-86.3%	kgC/m^2
The productivity of primary producers	0.081	0.099	22.3%	kgC/y/kgC
The zero displacement height of vegetation	1.0	0.25	-75.0%	m
The height of the mixing layer	9.5	0.90	-90.5%	m
The decomposition rate	0.91	0.80	-12.1%	1/y
The fraction of the decomposed carbon that is leaving as CO2 to the atmosphere	0.98	0.92	-6.2%	unitless
Productivity of human food				
The production of edible cereals	0.11	0.091	-20,2%	kgC/m^2/y
The production of edible vegetables	0.14	0.116	-14,1%	kgC/m^2/y
The production of edible root crop	0.13	0.11	-15,0%	kgC/m^2/y
The production of fodder on agricultural land	0.20	0.17	-14,0%	kgC/m^2/y
The ratio of leaf to soil surface area of vegetation	3.6	1.9	-48,1%	m^2/m^2
The production of edible fish in the lake	0.00027	3.2E-05	-88,0%	kgC/m^2/y
The production of edible crayfish in the lake	3.1E-05	0	-100,0%	kgC/m^2/y

a = normalized by the net lateral advective flux from the mire.

TABLE 44. PRODUCTIVITY OF EDIBLES IN DIFFERENT ECOSYSTEM TYPES

Ecosystem	Productivity kgC/m²/y	ha to support 1 person	People supported by 1 ha
Cropland			
Potato	2.00E-01	0.06	18.2
Sugar beet	1.80E-01	0.06	16.4
Field vegetables	1.48E-01	0.07	13.5
Cereals	7.40E-02	0.15	6.7
Peas	2.00E-02	0.55	1.8
Berries and fruit	2.00E-02	0.55	1.8
Forest	6.66E-04	17	0.06
Game	4.10E-05	268	0.00
Wild berries	1.13E-04	97	0.01
Mushrooms	5.12E-04	21	0.05
Mire	1.73E-04	64	0.02
Game	2.58E-05	427	0.00
Wild berries	1.22E-04	90	0.01
Mushrooms	2.56E-05	430	0.00
Coast	8.49E-05	130	0.01
Fish	8.47E-05	130	0.01
Waterfowl	1.40E-07	78571	0.00
Lake / river	5.34E-05	206	0.00
Fish	5.33E-05	206	0.00
Waterfowl	1.37E-06	8029	0.00

III.4. BIOSPHERE EVOLUTION MODELLING RESULTS FROM THE FORSMARK SITE

In the following, a brief summary is provided of the modelling performed to assess long-term radiological safety at the Forsmark site in Sweden. Groundwater flow has a key role in this context, due to its functions as a carrier of radionuclides and a "reaction environment" where processes altering the chemical compositions of the water take place. Therefore, the focus below is on hydrological modelling of the geosphere at the Forsmark site.

In the assessment of the Forsmark site, three different time periods are analysed: (1) the excavation and operational phases; (2) the initial period of temperate climate after closure of the repository; and (3) the remaining part of the reference glacial cycle; a summary of the modelling of these three periods is provided [93]. The excavation and operational phases are not further discussed here, but it should be noted that these phases, which are characterized by atmospheric pressure conditions in the repository and inflow of groundwater to it, are important for setting the chemical initial conditions for the following time periods.

The hydrogeological evolution during the temperate period after repository closure involves two distinct time intervals. The first is that for saturation of the repository once pumping of the open tunnels has ceased. The subsequent time interval deals with the evolution of the saturated repository during the remaining part of the period with temperate climate conditions. The actual impacts primarily depend on the permeability distribution of the bedrock (fracture network connectivity and hydraulic properties of the fractures), the repository layout and the associated permeability of the backfilled tunnels, and the prevailing boundary conditions. At Forsmark, the primary hydraulic driving forces for groundwater flow during periods with temperate climate conditions are flushing of terrestrial areas due to precipitation combined with the ongoing shoreline displacement. In order to assess the magnitude of these impacts, groundwater flow simulations, based on the hydrogeological models developed as part of the Forsmark site description [94], were performed.

The evolution for the remaining part of the reference glacial cycle was handled in a more stylised manner within the hydrogeological analysis. Bedrock hydrogeology during periods with both periglacial (permafrost) and glacial climate conditions were addressed, but the analyses performed are more of a bounding nature than trying to accurately predict the future evolution. The actual impacts primarily depend on the permeability distribution (fracture network connectivity and hydraulic properties of the fractures), and the prevailing boundary conditions. The primary hydraulic driving force for groundwater flow during periods of periglacial and glacial conditions is the hydraulic gradient resulting from the existence of an ice sheet. In order to assess the magnitude of these impacts, groundwater flow simulations, based on the hydrogeological models developed as part of the Forsmark site description [94], were performed also for this period.

In the hydrogeological analysis of the initial temperate period, particles were released in steady-state velocity fields at times from 0 AD to 12 000 AD in the site-scale groundwater flow model. The repository was included in a simplified manner. The discharge points of particles released at earlier times (0 AD, 1000 AD and 2000 AD) are located onshore near the repository and show a very slight migration toward the 2000 AD shoreline with release time. The near-future exit points (3000 AD, 4000 AD and 5000 AD) follow the retreating shoreline. The far-future exit points (6000 AD through to 12 000 AD) congregate on the north-eastern model boundary. This may be interpreted such that the model domain should be extended further to the northeast. However, the boundary is consistent with the boundary of the site descriptive model [95] and also corresponds to a bathymetric depression in the terrain. Thus, extending the model domain would not necessarily change the discharge location pattern. Furthermore, a minor change in discharge locations would not affect the derived biosphere discharge areas used in subsequent radionuclide transport and calculations.

It is demonstrated that the groundwater flux in the starting locations and properties along the flow paths (travel time and flow-related transport resistance) are essentially unchanged between different release times [96]. However, flow paths tend to become longer as the shoreline is displaced. This generally implies longer travel times and larger flow-related transport resistance values with time.

The primary driving force for groundwater flow at repository depth during periods of periglacial (permafrost) and glacial climate conditions is the hydraulic pressure gradient resulting from the existence of an ice sheet. The expected effects of this gradient with relevance for long-term safety are related to the groundwater chemistry, the performance measures of groundwater flow at repository depth, the advective travel time, and the flow-related transport resistance. In order to assess these impacts, groundwater flow simulations were performed [96, 97]. The overall objective of these simulations was to assess the effects of periglacial and glacial climate conditions on site hydrogeochemical and hydrogeological conditions in the presence of a backfilled repository.

Regardless of the case studied, an ice sheet without permafrost or an ice sheet with permafrost, a number of particles recharge at the upstream boundary of the model domain, which suggests that the model domain is too short to give a fully undisturbed view of all recharge locations. Nevertheless, it may be concluded that the present day topographic water divides, which play an important role for the recharge and discharge during temperate conditions, are significantly diminished in significance during glacial conditions. In contrast, the discharge locations are predominantly found well within the physical boundaries of the model domain and often very close to the margin of the ice sheet. The differences seen in the discharge pattern between the two glacial cases studied are largely caused by the alternative hydraulic properties and boundary conditions. The uncertainty in the occurrence of taliks, which may act as major discharge areas in the case of permafrost in the periglacial area in front of the ice sheet margin, is discussed in a climate report prepared by SKB [98].

An advancing ice sheet with permafrost ahead is considered a more realistic case than an ice sheet without permafrost. However, neither of the two permafrost cases studied gives significantly different results from the base case, i.e. an advancing ice sheet without permafrost [97].

The above type of discussion can, with appropriate detailed consideration, provide for a storyboard description of biosphere evolution at a site, as illustrated in the following for Forsmark.

III.4.1. The Forsmark biosphere storyboard

After the present temperate period (after 10 000 AD) [1, 2], a relatively short period of periglacial conditions will follow. The periglacial conditions will once again change back to temperate conditions that more or less will continue until 25 000 AD. Another temperate period is expected around 40 000 AD that will last for about 5000 years. During far-future temperate conditions, Forsmark will have characteristics that mimic the late parts of the initial temperate period. This means that there will be a landscape that comprises terrestrial ecosystems with few or no lakes and no sea. The terrestrial system will consist of forests, mires and areas possible for agriculture. Higher altitude areas with outcrops of bedrock will be forested with pine.

Periglacial periods are characterized by tundra vegetation and permafrost features. The precipitation is low, due to the limited evaporation transporting water to the atmosphere. The low evaporation means that wet ground is prevalent and the surplus water is unable to seep into the ground because of the permafrost. This results in extensive wetlands, but the amount of peat formed is negligible because plant productivity is low. The tundra is devoid of forests. The vegetation consists of herbs and shrubs, at raised dryer places lichens dominate and on wet ground mosses. The vegetation period is short.

The major part of the vertebrate fauna of the tundra migrates south during winter. The birds that are abundant during summer migrate over long distances to sub-tropical areas. Small mammals e.g. lemmings, do not migrate and spend most of their life under the isolating snow-cover grazing.

Even on gentle slopes, the soil slips downhill with the peat cover on top, i.e. solifluction occurs. Other processes are upward migration of stones induced by freeze-thaw processes, causing tundra-polygons and thermokarst phenomena. Thus, there are many processes disturbing the soil and also exposing it to erosion.

Taliks, i.e. unfrozen areas in the permafrost region under lakes or rivers, are potentially places which animals and humans can settle. However, even if the taliks can be potential locations for human settlement, the low productivity in the permafrost region requires utilization of a large area to supply the resources needed by even a small community. The talik feature is also of interest when constructing conceptualizations of transport of matter from the bedrock to the surface system.

During glacial periods Forsmark will be covered by an ice sheet. At the ice-margin, a productive aquatic community may exist. This can sustain a fish population which can be exploited by the animals living on the ice (e.g. birds, polar foxes, polar bears) and humans. The populations of vertebrates and humans are likely to migrate over large areas due to low food productivity or severe weather conditions. In most cases, a human population will probably comprise occasional visitors, due to the hostile environment and the variable ice-situation. It is possible that a human population could be present for longer periods close to the ice margin along the coast and live on fish.

In the reference glacial cycle, two periods of submerged conditions are identified. During these periods, Forsmark is covered by sea. The submerged conditions follow always directly after the ice sheet has withdrawn and the Forsmark bedrock is depressed by the ice load. After the last glaciation that ended in 8800 BC at Forsmark, the first terrestrial areas appeared around 1000 BC. The last areas in the Forsmark landscape that will turn terrestrial are calculated to do so at around 11 500 AD. This means that the submerged conditions will have two phases, one first phase of ca 8000 years when the whole area is submerged, and one that continues for 12 000 years when the sea gradually withdraws and the land area accordingly expands.

III.5. ILLUSTRATIVE RESULTS FOR EFFECTS ON CLIMATE CHANGE ON DOSES (BDCFS)

The following illustrations apply to a Baltic coast site rather than to Forsmark specifically.

Variation in land uplift and sea level mean that the ecosystem at the receiving end of a release from the geosphere changes with time. Figure 26 presents illustrative Ecosystem Dose Conversion Factors (EDFs, practically equivalent to the BDCFs) for example receptors from the BSA-2009 landscape model [99]: release directly to the receptor object, typical areas, and maximum dose to the most exposed individual getting his/her entire intake from the object regardless of its productivity of edibles. 'Lake+' denotes that the lake includes also its terrestrialized shoreline areas. Note that, except for C-14, any terrestrial object has a much higher dose than the aquatic types (see Table 44). Also, aquatic areas support fewer people per unit area than mire or forest - not to mention cropland.

Figures 27 to 29 show the time evolution of BDCFs for Ra-226, I-129 and C-14 respectively, for a specific scenario for climate change.

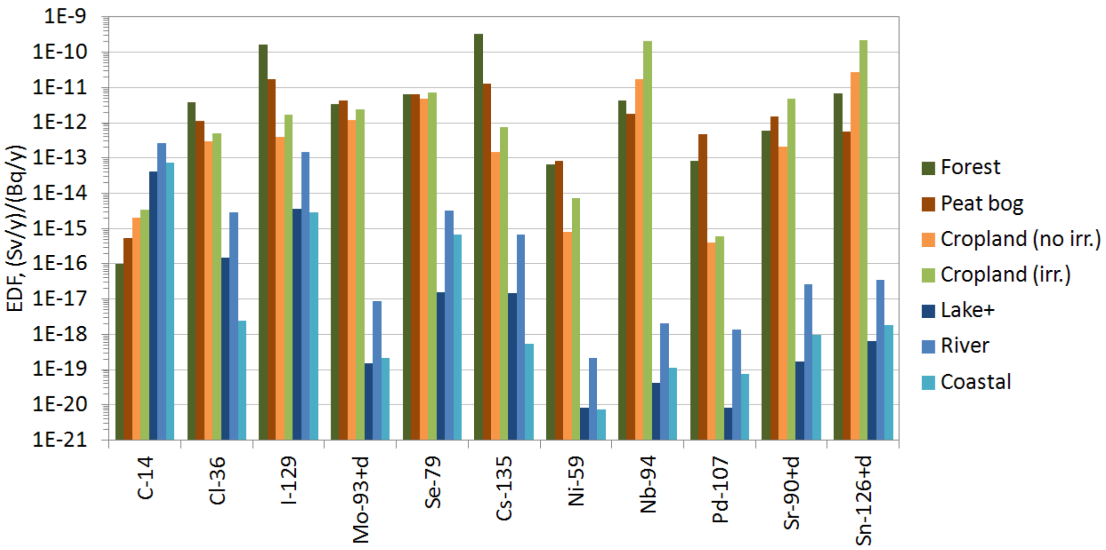

FIG. 26. Illustrative results of BDCFs (here called EDF) for releases to different ecosystems. Nuclide names appended with '+d' denote that also the relevant daughter nuclides have been included in the dose calculation. Croplands have been simulated for both non-irrigated ('no irr.') and irrigated ('irr.') variants; in the latter the irrigation water is taken from the 'Lake+'.

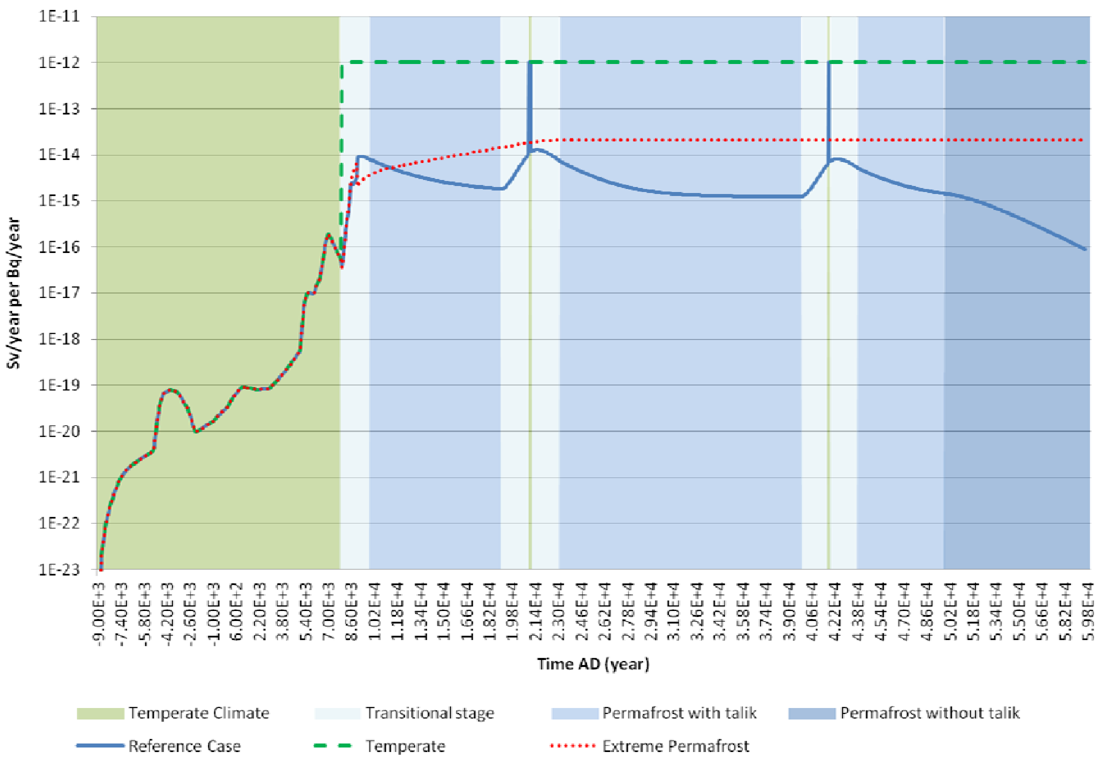

FIG. 27. Time evolution of BDCF for Ra-226.

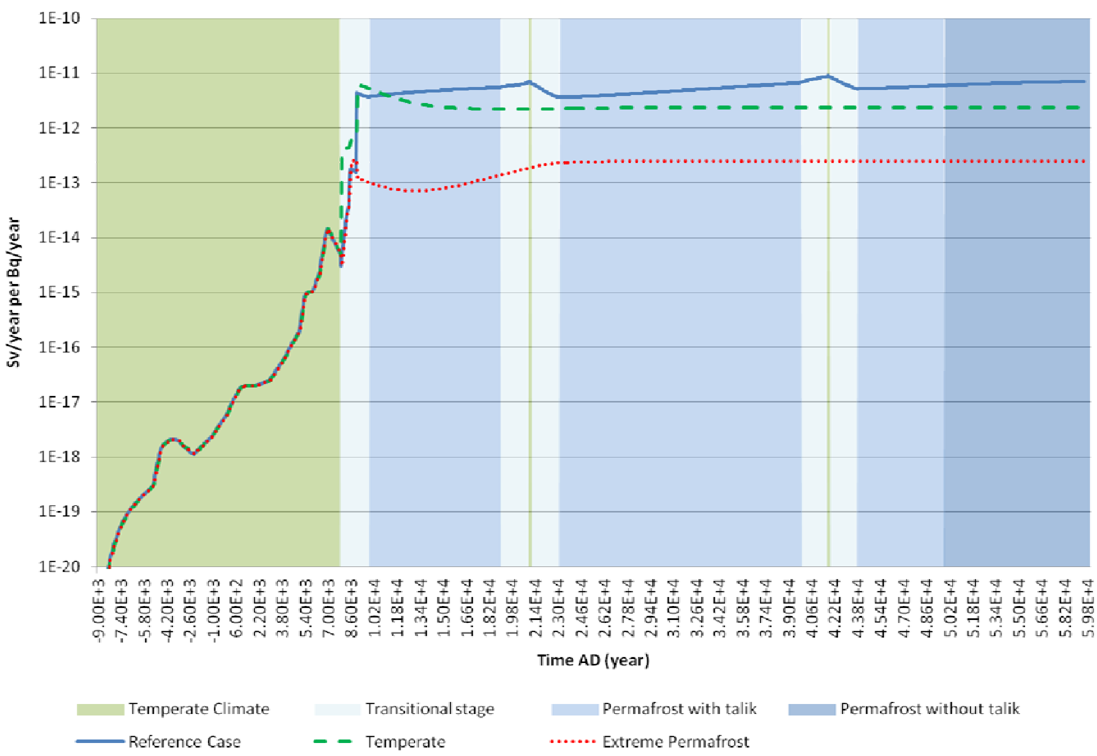

FIG. 28. Time evolution of BDCF for I-129.

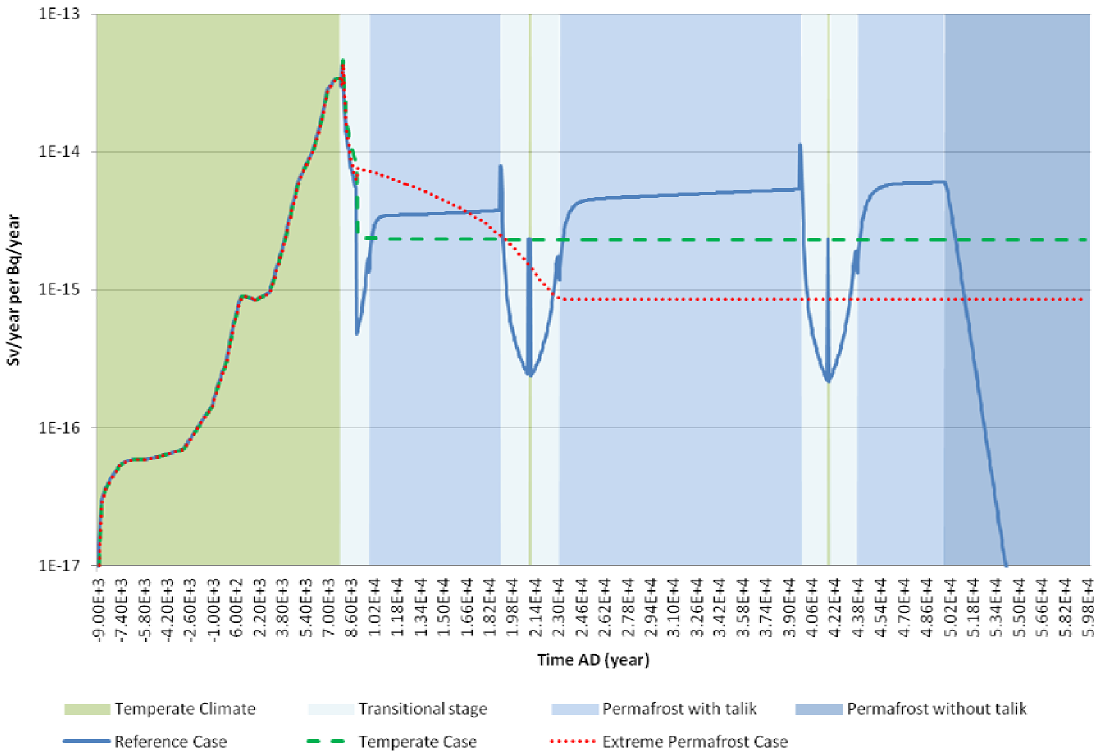

FIG. 29. Time evolution of BDCF for C-14.

III.6. SITE SPECIFIC PROCESSES OF GENERIC INTEREST

After defining all site specific processes, we used the interaction matrix to pinpoint those processes that are of general interest for environmental change. We also listed processes derived from global models. The description of the development of the biosphere uses information from the climate descriptions. The long-term climate-driven processes that affect Forsmark define the types of ecosystems that develop in time. The landscape develops from a state of a submerged marine ecosystem after a glaciation, via a landscape succession containing coastal, lake and wetland ecosystems, to a Forsmark that is dominated by forest and terrestrial ecosystems. The long-term landscape development at Forsmark is thereby driven by the global climate and processes originating from global climate, like the shoreline displacement. For a comprehensive description of the climate models and assumptions made concerning climate [100].

The modelling of a possible future is done by using the climate domains defined. We have used the main processes and features associated with the climate domains defined in the SKB reference glacial cycle [100] to describe the landscape development domain by domain. Supporting calculations of transitions between temperate and periglacial domains have also been undertaken. The outputs from these descriptions are then used in the overall merged development model, describing the landscape of Forsmark during a glacial cycle.

Many of the analyses of future environments within SKB are focused on the development of today's landscape influenced by the transgressing shoreline which divides the area into a submerged and a terrestrial part. This approach is valid for any area on earth affected by global shoreline displacement +/- 150 meters deviation from present shoreline.

The landscape geometry can be seen as a common platform for models used in landscape modelling at SKB. All other models and descriptions rely on a good geometric knowledge. We have used a number of data sources to build a digital elevation model (DEM) valid for the present situation. This model is then used together with data from the soil/sediment depth to construct a bedrock surface model and a model describing the stratigraphy of soils and sediments.

To make a realistic description of landscape development at Forsmark during a glacial cycle, the sedimentation and erosion processes in aquatic (marine and limnic) ecosystems have to be taken into account. In this work, a coupled regolith-lake development model was developed and applied to the Forsmark area. The model consists of two modules: a marine module that simulates sediment dynamics (erosion, transport and accumulation) in the sea (including the periods with fresh water in the Baltic) and a lake module that simulates lake ontogeny. In addition, two sub-models have been constructed: a sub-model that predicts generation of small wetlands that do not originate from infilled lakes and a sub-model that calculates export of fine-grained particles out of the model area. The sediment dynamics (accumulation/erosion) is a general and important process when building a model describing future environmental changes for a given site.

Table 45 lists the processes and features that we have identified as of common interest for a safety assessment handling environmental change at a specific site.

TABLE 45. COMMON PARAMETER/PROCESS TABLE FOR ENVIRONMENTAL CHANGE

Parameter/process	Temperate	Global warming	Periglacial	Glacial	Handled in radionuclide model	Importance in climate change	How to implement and comments
Period with ice coverage (days)	141 * (98-143)	1-2 months shorter	Several months longer	365	Yes	Yes	Make sure you have the right value for lake degasing when changing from temperate to other climate. There are some additional things to consider, like water residence time
Phosphorus concentrations (mg L^{-1})	0.01 * (0.004-0.04)	Probably higher	Probably lower	lower	No	Yes	Is handled by "production"
DOC concentrations	17 * (4.2-33)	Similar to present, higher or lower	Probably lower	Lower	No	Yes	Change Kd value (DOC sensitive) for climate sorption/desorption
Periods with anoxia	Only in very shallow lakes	Lower risk of anoxia in winter,	Probably in winter in shallow lakes		No	Yes	Caused by species composition and results in change of water composition. Change production and Kd values according to climate type
Phytoplankton biomass (g C m-3)	0.04 * (0.02-0.06)	Similar to present, higher or lower	Similar to present	Lower	Yes	No	Needs further discussion, not obvious that the parameter is of importance. Is handled in the parameter "productivity"
Benthic macroalage and macrophytes (gC m^{-2})	22 * (11-134)	Similar to present, higher or lower	Similar to present	Lower	Yes	No	Is handled in the parameter "productivity"

TABLE 45. (CONTINUED)

Parameter/process	Temperate	Global warming	Periglacial	Glacial	Handled in radionuclide model	Importance in climate change	How to implement and comments
Bacterioplankton biomass (gC m^{-3})	0.05 *	Similar to present, higher or lower	Similar to present or lower	Lower	Yes	No	Is handled in the parameter "productivity"
Zooplankton biomass (gC m^{-3}),	0.06 * (0.02-2.3)	Similar to present, higher or lower	Probably lower	Lower	Yes	No	Is handled in the parameter "productivity"
Fish biomass(gC m^{-2})	1.0 * (0.5- 1.6)	Similar to present, higher or lower	Lower	Absent	No	No	Not of importance for dose but for the number of people getting the dose
Pelagic Primary production (gC m-2 y^{-1})	16 * (10-19)	Similar to present, higher or lower	Lower	Lower	Yes	No	Handled via the power plant
Benthic primary production by macroalgae (gC m-2 y-1)	87 *	Similar to present, higher or lower	Similar to present or lower	Lower	Yes	No	Handled via the power plant
Pelagic respiration (at 1 m depth) gC m-2 y-1	74	Higher	Lower	Lower	Yes	No	Handled via the power plant
Benthic respiration	73	Higher	Lower	Lower			Handled via the power plant
Soil degasing					Yes	Yes	Handled in the model by terrestrial degassing
Evaporation					No	Yes	Could be of importance, e.g. high NaCl in lakes at Greenland
Permafrost					Yes	Yes	The model switches of the flow from regolith low, but is there a better way?
Land use					Yes	Yes	
cryoturbation					No	Yes	Could be of importance
Kd					No	Yes	Define a Kd suitable for the environmental condition
Mixing layer/lower atmosphere					Yes	Yes	Define a parameter value suitable for the environmental condition
Shore line displacement					Yes	Yes	Define a parameter value suitable for the environmental condition. This may lead to ecosystem change
Infilling					Yes	Yes	Define a parameter value suitable for the environmental condition. This may lead to ecosystem change
Water fluxes					Yes	Yes	If you have a system with open boundaries
Well					Tes	Yes	A well may not be operable during the permafrost period
Bioturbation					Yes/No	Yes	The process affected by climate. This is not handled
Food supply					Yes	Yes	No agricultural production during permafrost conditions
Transpiration					Yes/No	Yes	Define a parameter value suitable for the environmental condition.
Water uptake							Define a parameter value suitable for the environmental condition.
Active layer					No	Yes	The active layer properties are needed to describe surface processes, like transport. Maybe a new box in the model or processes between boxes that change. Background models that take seasonal variations into account
Seasonal variation patterns							Seasonal patterns that are averaged in the model should be assessed for the climate you describe
Decomposition					Yes	Yes	Mainly for C-14 modelling

III.7. CLIMATE-RELATED GEOSPHERE CHANGES AFFECTING THE BIOSPHERE ASSESSMENT

III.7.1. Overview of processes

The geosphere assessment includes a multitude of analyses dealing with processes of potential significance for the biosphere modelling. For example, modelling within disciplines such as hydrogeology, geology, hydrochemistry, geochemistry and rock mechanics describe conditions and future changes of the geosphere that may be important when describing effects of long-term climate variations in the biosphere assessment. However, in a safety assessment based on the presently considered release and transport scenario, i.e. radionuclides released to and transported by flowing groundwater through the geosphere with retention due to combined physical and chemical processes taking place along the flow paths, the main, partly inter-related changes can be identified as follows.

— Changes in where radionuclides are discharged. This refers to changes in the locations or areas where radionuclide-containing groundwater leaves the geosphere and enters the biosphere. In a dynamic system affected by sea level changes and for which significantly different climate domains need to be considered, discharge locations may change due to shoreline displacement and presence of permafrost or an ice sheet. These factors may have profound effects on flow boundary conditions and hydraulic properties, thereby possibly altering large-scale flow patterns and/or detailed flow paths associated with specific hydrological objects.

— Changes in when radionuclides are discharged. In this case, the focus is on the timing of the radionuclide discharge from the geosphere, as affected by changes in groundwater flow. If the groundwater flow system changes, due to changes in boundary conditions and/or hydraulic properties, this may affect the time needed for radionuclide-containing water to be transported through the geosphere, and hence also the arrival time and temporal distribution of a radionuclide release from the geosphere to the to the biosphere. Changes in water residence times in the geosphere also change the conditions for solute exchange between fractures and matrix, and hence the effect of retention on radionuclide transport.

— Changes in what is being discharged. This refers to changes in the composition of the discharged water, potentially arising as consequences of processes such as radionuclide decay or chemical reactions in the aqueous phase or through interactions with solid phases. For instance, changes in water residence times lead to longer or shorter times being available for decay chains to transform radionuclides. If flow paths change, also the chemical conditions along them may change, which, in turn, could affect the chemical composition of the groundwater.

It follows that hydrogeology and hydrogeochemistry are the main modelling disciplines dealing with issues of importance for the biosphere assessment. However, the modelling within these disciplines is to large extent determined by geometric and geologic changes affecting basic model features such as boundary conditions and physical and chemical properties of the geologic materials. The analysis of climate-related changes concerns both developments within a specific climate domain, for example, the near-future changes occurring at coastal sites due to sea-level variations, and changes taking place when the system goes from one climate domain to another, for example, from the temperate to the periglacial domain.

When analysing discharge locations, sea-level changes and shoreline displacement under relatively constant (e.g. temperate) climate conditions determine the location of the coastline and the relative proportions of land and sea in the considered area. These conditions, in turn, determine some of the large-scale boundary conditions for flow. Changes in flow boundary conditions could affect locations and lengths of flow paths, as well as transport velocities and residence times along them. However, flow and transport in fractured rock is to large extent determined by structural geology (flow takes place in fractures and deformation zones), which means that the significance of changes related to shoreline displacement is site specific. If the flow system changes as a consequence of climate change (within or between climate domains), the most important issue to clarify is whether the overall discharge pattern changes such that different biosphere objects or areas could be affected by contaminated groundwater. However, also variations in detailed discharge patterns associated with specific objects could be of importance for the biosphere assessment.

Concerning factors affecting the time for contaminant release to the biosphere and the chemical composition of the contamination, the water residence time is an important parameter for some radionuclides. This is primarily the case for radionuclides not significantly affected by retention processes. The residence time determines the time available for radiological transformations and interactions with the matrix; a longer residence time provides a longer time during which radionuclide-containing water could diffuse into the matrix where sorption and other retention processes could further delay radionuclide transport.

However, flow paths could also change in space, such that they pass through geologic materials with different physical and/or chemical properties, thereby changing the composition of the water entering the biosphere. Clearly, the potential for changes of this kind is strongly related to the physical and geochemical heterogeneity of the system; if conditions are more or less similar in the whole system spatial variations would not have large effects of transport. In a fractures rock system, also changes in the physical configuration of the flow in the fractures could be important. The contact area between the flowing water and the matrix is an important parameter for the transfer of solute to the matrix, and hence also for the effect of retention due to processes in the matrix.

III.8. CONCLUSIONS AND DISCUSSION

Environmental change in a long-term perspective is dependent on few, and partly dependent factors: At the Forsmark site, the major forces are climate variations and shoreline displacement. These two factors in combination strongly affect a number of processes, which in turn determine the development of ecosystems. Some examples of such processes are erosion and sedimentation, groundwater recharge and discharge, soil formation, primary production and decomposition of organic matter.

Climate variations will directly change the conditions for ecosystem formation, e.g. the formation of wetland complexes, and cause north- and southward migration of species and ecological communities. Changes of species distributions have the potential of affecting whole ecosystems through the emergence or disappearance of species that may have a key function in the ecosystem

The second important factor for long-term environmental change at the site, shoreline displacement, is a secondary effect of climate variations. It is caused by the interaction between glacially induced isostatic depression/recovery on the one hand, and eustatic sea-level variations on the other. Periodically, shoreline displacement has strongly affected the

Forsmark area, both before and after the latest deglaciation. Accordingly, the area has repeatedly been situated below sea level for long periods.

At the time of the latest deglaciation of the Forsmark area around 8800 BC, the nearest shoreline was situated around 100 km west of Forsmark and the area was covered by approximately 150 m of glacio-lacustrine water. Thereafter, the isostatic rebound in the Forsmark area and in areas further north has been continuous and slowly declining. The rate of rebound in Forsmark has decreased from around 3.5 m/100 years directly after the deglaciation to a present rate of around 0.6 m/100 years, and it is predicted to decrease further to become insignificant around 30 000 AD.

This means that the shoreline displacement causes a continuing and predictable change in the abiotic environment, e.g. in water and nutrient availability. It is therefore appropriate to describe the origin and succession of some major ecosystem types in relation to shoreline displacement. One example of this is the isolation of a sea bay into a lake, the following ontogeny of the lake and its further development into a wetland.

The illustrative results show how the approach can be used to make a clear dynamic link between the points of radionuclide release from the geosphere to the temporally varying biosphere system above it. It also shows how this can be important for the assessment of doses. It is obvious that a more dynamic site is likely to need closer consideration of the dynamics of the system.

It can be understood that, where sufficient site understanding has been established, it is possible to focus in detail on the key issues and thereby, avoid what might otherwise have been more conservative assumptions. Climate scenario and development of the biosphere (and the rest of the system) can be handled with realistic/plausible examples of lines of evolution as it is practically impossible to assign specific probabilities to the lines of evolution or to cover the full range of possible futures - the strategy to avoid endless speculation is to choose an illustrative set of scenarios, relevant to the assessment context.

This gets then to the main factors of the lines of evolution, i.e. climate variation and shoreline displacement; how to remain "plausibly conservative" and not overly conservative. This depends on the interpretation of international recommendations, and on national requirements and guidance on related assessments, reviewed in SG4.

APPENDIX IV. DEMONSTRATION OF COMPLIANCE WITH PROTECTION OBJECTIVES

IV.1. INTRODUCTION

SG4 explored issues in compliance demonstration which are affected by the need to take account of environmental change.

Firstly, a review has been made in Section IV.2 of relevant international recommendations on protection objectives and guidance on corresponding assessment methods, as provided by the IAEA and the ICRP.

Then, in Section IV.3, examples of national level recommendations have been considered, to illustrate how international recommendations and guidance have been applied.

IV.2. INTERNATIONAL FUNDAMENTALS, REQUIREMENTS AND GUIDES

In reviewing international documentation, consideration was given to the following hierarchy:

- Fundamentals (F), understood as overarching objectives;
- Requirements (R), understood as technical interpretaion of the fundamentals;
- Guides (G), understood as advice on interpretation and compliance demonstration with the requirements.

The intention was to identify how the documentation proposes that environmental change should be addressed in post closure safety assessment for waste repositories and how that relates to the fundamentals. Potentially relevant are:

- requirements to consider environmental change;
- assumptions to be made about such change, e.g. key drivers of change;
- implications for construction of scenarios, with special reference to the definition of biosphere systems;
- key processes identified which need to be considered within those scenarios.

The IAEA Safety Fundamentals. Fundamental Safety Principles (SF-1) [101]

Principle 7 of SF-1 "Protection of present and future generations" says that "*people and the environment, present and future, must be protected*". This principle does not say anything about environmental change or how far into the future the objective applies, but it could be considered as a basis for consideration of the future in long-term assessments.

Safety Fundamentals, The Principles of Radioactive Waste Management [102]

"Principle 2: Protection of the environment. Radioactive waste shall be managed in such a way as to provide an acceptable level of protection of the environment."

In comments to this principle, the IAEA recognizes that radioactive waste disposal may have negative effects not only on the "*future utilization of natural resources like land, forests, surface waters, groundwater, raw materials*", but also their "*availability over extended periods of time*".

"Principle 4: Protection of future generations. Radioactive waste shall be managed in such a way that predicted impacts on the health of future generations will not be greater than relevant levels of impact that are acceptable today."

Here the IAEA brings attention to the necessity of taking into account uncertainties in long term safety assessment due to the difficulty in predicting impacts far into the future. This is similar to Principle 7 of SF-1 [101], but is importantly different in requiring that impacts on future generations will not be greater than those acceptable today, as opposed to be protected. The Safety Fundamentals [102] was subsumed within the more broadly based SF-1 [101], but the reasoning behind this particular change was not explicit therein.

ICRP Publication 81, Radiation protection recommendations as applied to the disposal of long-lived solid radioactive waste [103]

ICRP Publication 81 notes that there are *"some natural processes"* which may *"result in a gradual release of radionuclides to the environment". After "the gradual degradation of the waste package due to corrosion"* natural processes that could lead to human exposure may include *"transport of radionuclides by groundwater with the associated processes of sorption, diffusion and dispersion"*. They also mention *"less likely, natural processes" ("e.g. seismic events and glaciations")* which affect the performance of the disposal system. This could be considered as an ICRP recommendation regarding key processes which might need to be considered in disposal safety assessment or as a recommendation that natural process have to be considered in general. They also note that *"Human actions in the future may also disrupt a waste disposal system."*

In ICRP Publication 81 [103], the Commission does not say anything about timeframes of safety assessment but recognizes the inherent uncertainty and the problems of estimating individual doses and the size of the exposed population over long periods of time in the future.

"In the context of protecting future generations, the relevant indicators are the annual individual dose to a critical group for normal exposure and the annual individual risk to a critical group for potential exposure." The Commission also recommends *"a value of no more than about 0.3 mSv per year for the dose constraint for members of the public from radioactive waste disposal activities"* which *"corresponds to a risk constraint of the order of* 10^{-5} *per year"*. It is applicable in normal exposure situations. This means that annual individual dose as well as annual individual risk could be considered as the main output data of post-closure safety assessment for waste repositories which then (in case of estimates for times beyond around several hundreds of years) could be compared with appropriate criteria *"to give an indication of whether the repository is acceptable given current understanding of the disposal system"*. Demonstration of compliance with the radiological criteria thus includes a demonstration of understanding of the disposal system.

The ICRP states that *"...permanent total isolation is not likely to be achievable and some fraction of the waste inventory may migrate to the biosphere, potentially giving rise to exposures hundreds or thousands of years in the future"*. This could be interpreted as a suggestion that safety assessment has to be made at least for this (100s – 1000s years) period of time after closure. The comment is also consistent with the IAEA Safety Glossary [104] definition of containment, i.e. *"Methods or physical structures designed to prevent or control the release and the dispersion of radioactive substances"*. It is clear that environmental change may occur over such periods.

Assumptions for human behaviour and dietary habits are among the core aspects of biosphere modelling which can influence significantly the assessed exposure which can strongly change in time due to a variety of reasons, for instance: technical, economical and agricultural development, as well as wide environmental change. However, the Commission says that "*the habits and characteristics assumed for the critical group should be chosen on the basis of reasonably conservative and plausible assumptions, considering current lifestyles as well as the available site or region specific information.*" It is also important to remember in development of assessment models the "*different scenarios associated with different critical groups*".

For a critical group and biosphere definition the Commission suggests using *"either a site specific approach based on current available site or regional information or a stylized approach based on more general habits and conditions; the use of stylized approaches will become more important for the longer time-scales"*. It may be noted that a site specific approach cannot be used for a site generic assessment, and so the stylized approach may also be useful at early periods in that case. Since sites are less likely to have been identified, or even if they have, only partially characterized, the stylized approach may be more appropriate in the early stages of repository development.

The ICRP Publication 81 [103] says that *"major changes may occur in the biosphere in the long-term due to the action of natural forces in a similar manner to those occurring in the past. ... Consideration of biosphere changes should be limited to those due to natural forces"*. This could be taken to mean that natural climate changes, which are logically connected with the term 'natural forces', have to be taken into account for biosphere modelling purposes. However, the assumptions about these changes should, according to this approach, be based only on past climate change which occurred prior to human impacts on climate. The approach explicitly proposes not taking account of human induced change, and hence human induced climate change.

The Commission also suggests:

- *"to assume that radioactive contamination of the biosphere due to releases from the repository is likely to remain relatively constant" over the time of consideration;*
- *"to calculate the annual dose/risk averaged over the lifetime of the individuals" "this average can be adequately represented by the annual dose/risk to an adult".*

This appears to support the idea of not addressing doses to other age groups than adults, but it is not so clear what is meant by relatively constant, and appears, without explicit justification, to argue against taking account of relatively short term changes, even if they implied bigger doses.

One of the Commission's judgments is that *"to evaluate the performance of waste disposal systems over long time scales, one approach is the consideration of quantitative estimates of dose or risk on the order of 1000 to 10 000 years. This approach focuses on that period when the calculation of doses most directly relates to health detriment and also recognizes the possibility that over longer time frames the risks associated with cataclysmic geologic changes such as glaciation and tectonic movements may obscure risks associated with the waste disposal system. Another approach is the consideration of quantitative calculations further into the future making increasing use of stylised approaches and considering the time periods when judging the calculated results."* It could be concluded that post-closure safety assessment for waste repositories has to be made for 1000 to 10 000 years and environmental changes (and in particular geologic changes) have to be taken into account. It may be noted that changes in surface and subsurface groundwater flows due to climate change might be among the environmental changes of interest.

Radiological Protection in Geological Disposal of Long-Lived Solid Radioactive Waste Draft Report for Consultation [105]

The ICRP consultation document on geological disposal, intended in part ,to replace ICRP Publication 81 [103] in due course[10], notes the following:

> *1. Line 1204: A representative person cannot be defined independently of the assumed biosphere. Major changes may occur in the biosphere in the long-term due to the action of natural forces in a similar manner to those occurring in the past. Human actions may also affect the biosphere, but one can only speculate about human behaviour in the long-term. In the definition of the scenarios, consideration of biosphere changes should be limited to those due to natural forces.*

This appears to rule out the effect of climate change due to man-made global warming, unless man is taken to be part of the natural environment. It might be unreasonable to require consideration of a potentially unlimited variety of possible human behaviours, including technology developments [106]. Given current concerns for, and the potential scale of, climate change, it would seem prudent to take this into account in repository PAs.

Specific Safety Requirements, Disposal of Radioactive Waste (SSR-5) [107]

This requirements document says that the safety objective of radiation protection in the post-closure period in SSR-5 sounds like *"a reasonable assurance has to be provided that **doses and risks** to members of the public in the long term will not exceed the dose constraints or risk constraints that were used as design criteria"*. This complements ICRP Publication 81 [103] and could be interpreted as saying that dose and risk to members of the public are the main quantitative indicators of post-closure safety assessment for waste repositories.

The sentence *"To comply with the dose limit, a disposal facility (considered as a single source) is so designed that the calculated dose or risk to the representative person who might be exposed in the future as a result of possible natural processes affecting the disposal facility does not exceed a dose constraint of 0.3 mSv in a year or a risk constraint of the order of 10^{-5} per year"* points at the same values of dose and risk constraints as ICRP Publication 81 [103]. In contrast to ICRP Publication 81 [103], SSR-5 [107] requires assessment of dose or risk to the representative person, as ICRP Publication 103 [34] recommends, and not to the members of the critical group. However, ICRP Publication 103 [34] also says that guidance in ICRP Publication 81 [103] still stands, implying the continued use of critical groups. The quoted phrase shows the necessity to consider environmental and climate influence.

As well as dose and risk to the representative person IAEA SSR-5 [107] suggests additional indicators and comparisons, such as *"concentrations and fluxes of contaminants and their comparison with concentrations and fluxes of radionuclides of natural origin within the*

[10] Since this report was prepared, the final version of ICRP guidance has been published on geological disposal of long-lived solid radioactive waste, as ICRP Publication 122 [108]. However, the wording above has been retained.

geosphere or biosphere". The advantages of such indicators are that they do not include the uncertainty associated with habits of people and can be complementary safety indicators to dose and risk for assessments at long times after closure.

SSR-5 [107] notes the following with respect to uncertainty: *"It is recognized that radiation doses to people in the future can only be estimated and that uncertainties associated with these estimates will increase for times farther into the future. Caution needs to be exercised in applying criteria for periods far into the future."* The emphasis is on dose estimation rather than predictions, as per Principle 4 of the Safety Fundamentals [102].

The Requirement 9 (Isolation of radioactive waste) of SSR-5 [107] *"The disposal facility shall be sited, designed and operated to provide features that are aimed at isolation of the radioactive waste from people and from the accessible biosphere. The features shall aim to provide isolation for several hundreds of years for short lived waste and at least several thousand years for intermediate and high level waste."* could be considered as IAEA recommendation that at least for these periods of time (1000s years) the post-closure safety assessment for geological disposal facilities must be implemented.

Specific Safety Guide, Geological Disposal Facilities for Radioactive Waste (SSG-14) [109]

Like the above-mentioned documents this guidance document says that *"for the most highly concentrated radioactive waste ... it is necessary that the engineered barriers provide practically complete containment over a period of several hundreds of years to several thousand years"*. This could be considered indicative of IAEA's guidance concerning timescales for post-closure safety assessments for geological waste repositories.

In appendix "Post-closure safety assessment" SSG-14 [109] notes *"Assessments may need to project the behaviour of the site and facility for time periods of the order of thousands of years and potentially longer"*.

SSG-14 [109] says that *"the safety case for the period after closure should be based on quantitative analyses and should be further supported by qualitative arguments. It may include the presentation of multiple lines of reasoning based, for example, on studies of natural analogues and palaeohydrogeological studies"*. This statement could be considered as IAEA's recommendation that assumptions taken when making safety assessment and biosphere modelling should base on natural processes observed in the past including interactions of groundwater with rocks, surface water and atmosphere as well as other interactions in environment. In other words these natural processes are key processes which need be considered within scenarios.

SSG-14 [109] suggests to give attention to uncertainty concerned with safety assessment (two sources of uncertainty: reality and correctness of model; unpredictability of the evolution of the facility and its environment over long periods of time).

Requirement 15 of SSG-14 [109] related to site characterization for a disposal facility states: *"The site for a disposal facility shall be characterized at a level of detail sufficient to support a general understanding of both the characteristics of the site and how the site will evolve over time. This shall include its present condition, its probable natural evolution, and possible natural events and also human plans and actions in the vicinity that may affect the safety of the facility over the period of interest…"*

"… knowledge from site characterization will be necessary to provide a credible scientific description of the natural characteristics at the site and a demonstration of understanding concerning safety significant processes (e.g. geological, hydrological, geochemical, mechanical processes)." The significant processes (geological, hydrological, geochemical, mechanical) could be taken as among key processes which need to be considered within safety assessment scenarios.

In support of models describing the evolution of the site SSG-14 [109] requires to investigate *"the long term stability of the geosphere in response to past environmental and climate changes at the surface and the effects of tectonics, including faulting, rock fracturing and volcanism". "Palaeohydrogeological studies are particularly relevant in this regard. The time scale for consideration of such changes should be at least comparable to the future time scale of interest in safety assessment. Such information may be used in support of scenarios for the future natural evolution of the site and for evaluating the relevance of features, events and processes that could affect the performance of the disposal system, including interactions between the natural and engineered elements."*

Appendix I of SSG-14 [109] is dedicated to site investigation, characterization and data needed. Necessary data include: site characteristics (geology, hydrogeology, geochemical properties, climate conditions); biosphere characteristics (natural habitat, atmospheric conditions, aquatic conditions); demographic and socioeconomic characteristics (land use, food habits, population distribution) and others. These data should be used to support safety assessments or environmental impact assessments.

SSG-14 [109] says *"Climate evolution represented by glacial cycles may result in fundamental changes in the Earth's hydrosphere, such as fluctuations in sea level, changes in erosion or sedimentation processes and rates, changes in glacial or periglacial conditions, and variations in the surface and subsurface hydrological balance. Geodynamic effects such as ground motion associated with earthquakes, land subsidence and uplift, volcanism and diapirism may also induce changes in the Earth's crustal conditions and processes."* This could be considered as saying that climate evolution and geodynamic phenomenon are either the principle, or among the principle, drivers of environmental change and effect of these phenomena should be taken into account when carrying out post-closure safety assessments.

SSG-14 [109] identifies few pathways which *"are likely to be important for the undisturbed performance of a disposal facility. They include groundwater transport, soil, land plants, land animals, surface waters, aquatic animals and gaseous pathways."* This implies that transport of radionuclides from one system to another one, uptake by plants and animals as well as other relevant processes which take place within each system have to be considered within scenarios.

> *Line 1263: Over the long time frames that are considered in waste disposal, the biosphere is likely to change, and even change substantially. Such changes entail biosphere evolution with time that is either natural, or enhanced or perturbed through human action. Contributing factors may be, e.g., climate change including glaciations cycles, and land uplift or depression. Understanding different biospheres today and assessing impacts in such biospheres based on an approach involving Reference Animals and Plants, may guide our understanding of future biosphere changes also for the purpose of environmental protection.*

This latter refers to environmental protection, and appears to go further with respect to environmental change than that in relation to human protection.

Specific Safety Guide SSG-23, The Safety Case and Safety Assessment for the Disposal of Radioactive Waste [110]

The theme developed in the above documents concerning environmental change is developed further [110] for example:

"The system description should contain, depending on the type of disposal facility, information on the following: {among other things} The biosphere, e.g. climate and atmosphere, water bodies, the local population, human activities, biota, soils, topography and the geographical extent and location of the disposal facility."

And:

"The description of the disposal system should include the following: {among other things} The biosphere, e.g. climate and atmosphere, water bodies, the local population, human activities, biota, soils, topography and the geographical extent and location of the disposal facility."

Note that the system is taken to include the biosphere according to the above. Since characterisation of the biosphere can only take place meaningfully on a site specific basis, approaches to characterisation of the biosphere have only more recently received attention [111].

SSG-23 [110] also suggests that the system description should include:

"A clear specification and description of the components of the system and their interfaces and associated uncertainties;"

This implies the need to consider carefully processes and events at the interface between the far field of the geosphere and the biosphere, as discussed in other literature [112].

SSG-23 [110] goes on to say:

"When assessing the safety of a waste disposal facility, it is important to consider the performance of the disposal system under both present and future conditions. This means that many different factors (e.g. future human actions, climate and other environmental changes as well as events or processes that could affect the performance of the disposal facility) need to be taken into account."

This text further emphasizes the need to consider environmental change, but, in this case, including those due to future human actions.

IV.3. EXAMPLES AND DISCUSSION OF NATIONAL APPLICATION OF INTERNATIONAL FUNDAMENTALS, REQUIREMENTS AND GUIDES

The following is intended to be illustrative of key points rather than a comprehensive review. The intention is to provide examples of how issues have been addressed in regulatory requirements at the national level.

IV.3.1. Sweden

IV.3.1.1. Protection of human health

The Swedish regulations on the Protection of Human Health and the Environment in connection with the Final Management of Spent Nuclear Fuel or Nuclear Waste [113] states that a repository for spent nuclear fuel or nuclear waste shall be designed so that the annual risk of harmful effects after closure does not exceed 10^{-6} for a representative individual in the group exposed to the greatest risk.

IV.3.1.2. Time periods

The regulations [113] also state that an assessment of a repository's protective capability shall be reported for two time periods; the first thousand years following repository closure and the period after the first thousand years following repository closure. The description shall include a case, which is based on the assumption that the biospheric conditions, which exist at the time that the application for a license to operate the repository is submitted, will not change. Uncertainties in the assumptions made shall be described and taken into account in the assessment of the protective capability. For the first thousand years following repository closure, the assessment of the repository's protective capability shall be based on quantitative analyses of the impact on human health and the environment. For the period after the first thousand years following repository closure, the assessment of the repository's protective capability shall be based on various possible sequences for the development of the repository's properties, its environment and the biosphere.

IV.3.1.3. Environmental Protection

Regarding environmental protection [113] states that the final management of spent nuclear fuel or nuclear waste shall be implemented so that biodiversity and the sustainable use of biological resources are protected against the harmful effects of ionizing radiation. Biological effects of ionizing radiation in living environments and ecosystems concerned shall be described. The report shall be based on available knowledge concerning the ecosystems concerned and shall take particular account of the existence of genetically distinctive populations such as isolated populations, endemic species and species threatened with extinction and in general any organisms worth protecting.

IV.3.1.4. Safety Assessment

The Swedish regulations on Safety in connection with the Disposal of Nuclear Material and Nuclear Waste [114] states that the safety assessments shall comprise features, events and processes which can lead to the dispersion of radioactive substances after closure, and such analyses shall be made before repository construction, before repository operation and before repository closure.

A safety assessment shall comprise as long time as barrier functions are required, but at least 10 000 years.

Appendix 1 of the regulations [114] states that the following shall be reported with regard to analysis methods: How one or several methods have been used to identify and describe relevant scenarios for sequences of events and conditions that can affect the future evolution of the repository; the scenarios shall include a main scenario that takes into account the most probable changes in the repository and its environment.

Appendix 1 of the regulations [114] also states that the following shall be reported with respect to the analysis of post-closure conditions: The safety assessment comprising descriptions of the evolution in the biosphere, geosphere and repository for selected scenarios; the environmental impact of the repository for selected scenarios, including the main scenarios, with respect to defects in engineered barriers and other identified uncertainties.

In the General recommendations included in the regulations [114] it is stated that the time period for which safety has to be maintained and demonstrated should be a starting point for the safety assessment. One way of discussing and justifying the establishment of such a time period is to start from a comparison of the hazard of the radioactive inventory of the repository with the hazard of radioactive substances occurring in nature. However, it should also be possible to take into consideration the difficulties of conducting meaningful analyses for extremely long time-periods, beyond one million years, in any other way than through showing how the hazard of the radioactive substances in the repository declines with time.

In the case of a repository for long-lived waste, the safety assessment may have to include scenarios which take into account greater expected climate changes, primarily in the form of future glaciations. For example, the next complete glacial cycle which is currently estimated to be on the order of 100 000 years, should be particularly taken into account. In the case of periods up to 1000 years after closure the dose and risk calculated for current conditions in the biosphere constitute the basis for the assessment of repository safety and its protective capabilities. Furthermore, in the case of longer periods, the assessment can be made using dose as one of several safety indicators. This should be taken into account in connection with the calculations as well as the presentation of analysis results.

Examples of such supplementary safety indicators are the concentrations of radioactive substances from the repository which can build up in soils and near-surface groundwater or the calculated flow of radioactive substances to the biosphere.

IV.3.2. Finland

According to the Finnish Government Decree GD 736/2008 [115], compliance with the long-term radiation protection requirements as well as suitability of the disposal method and site shall be demonstrated by means of a safety case, which covers both expected evolution scenarios and unlikely events impairing long-term safety. Furthermore, it is stated that the safety case comprises a computational analysis based on experimental studies and complementary considerations insofar as quantitative analyses are not feasible or involve considerable uncertainties.

The regulatory requirements for the long-term safety of disposal were given in the guide YVL 8.4[11] [116]. The guide gives the principles according to which the final disposal systems must be designed, built and operated. The guide gives the framework for the safety case which aims to prove the safety of the final disposal.

The guide defined the radiation safety requirements based on Nuclear Energy Act 990/1987 [117] and related legislation. For expected evolution scenarios:

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[11] Since this report was prepared, the legislation and related guides have been updated, but retain the key features mentioned above.

— *"the annual dose to the most exposed people shall remain below the value of 0.1 mSv;*
— *the average annual doses to other people shall remain insignificantly low."*

These constraints are applied for timescales for which the radiation exposure on humans can be estimated with sufficient reliability, for at least several millennia. The dose assessment shall take into account changes in the environment which result from the elevation of the sea level and land uplift. The climate type, human habits and needs can be presumed to stay unchanged. The analysis shall at least take into account the use of contaminated water and use of contaminated agricultural and natural products. For timescales exceeding several millennia, constraints on annual radioactive releases to the environment are imposed. The releases can be averaged over one thousand years.

The unlikely events that need to be analyzed are defined. These include at least: rock movements which may damage the canisters, drilling of a medium-deep water well on the disposal site, and core drilling or boring hitting a canister.

It is also stated that the disposal shall not affect detrimentally on non-human biota due to radioactivity. The radiation exposure caused to the non-human biota shall stay well below the levels which could cause decline in the biodiversity or cause notable harm to some biotic community.

In addition, there are radionuclide specific constraints for the radioactive releases to the environment (average release of radioactive substances per annum) referred to above are as follows:

— 0.03 GBq/a for the long-lived, alpha emitting radium, thorium, protactinium, plutonium, americium and curium isotopes;
— 0.1 GBq/a for the nuclides Se-79, Nb-94, I-129 and Np-237;
— 0.3 GBq/a for the nuclides C-14, Cl-36 and Cs-135 and for the long-lived uranium isotopes;
— 1 GBq/a the nuclide Sn-126;
— 3 GBq/a for the nuclide Tc-99;
— 10 GBq/a for the nuclide Zr-93;
— 30 GBq/a for the nuclide Ni-59;
— 100 GBq/a for the nuclide Pd-107.

IV.3.3. United Kingdom of Great Britain and Northern Ireland

Regulatory guidance is provided on requirement for assessment of geological disposal [118][12]. A key comment in the current context from this guidance is that:

"The environmental safety case needs to take into account the potential for climate change. Possible climate change may be induced by natural processes, or by human actions affecting natural processes. There is considerable uncertainty regarding the rate, amount and even the direction of possible climate change over different timescales. So, the developer/operator will

[12] This guidance does not apply in Scotland.

need to consider a range of possibilities. The potential consequences of climate change include changes in rainfall patterns (which can affect watercourses and aquifers), changes in sea level, increased rates of erosion including coastal erosion, glacial cycling and glaciotectonic movements."

IV.3.4. France

French regulatory requirements for geological disposal conclude that it is not possible to predict the local biosphere evolution for very long periods of time and introduces the concept of biosphere types, representative of the different biosphere states that could pertain during a long time period [119]. The biosphere-type concept entails glaciation and deglaciation periods. Furthermore, the situations to be assessed include climatic cycles, both of regular or large amplitude. the regulations specify a 10 000 year period for safety demonstration and that a 0.25 mSv/y dose constraint should apply. After that period they indicate that the uncertainties regarding evolution of the system increase and demonstrations covering the main individual exposures should be performed and complemented with some qualitative estimation of the evolution of the geological medium.

IV.3.5. United States of America

The function of the biosphere model is to support the Total System Performance Assessment for the proposed Yucca Mountain repository for high level waste, by providing the mechanism for calculating annual radiation dose to a receptor defined in the licensing rule arising from radionuclide concentrations in groundwater. "Receptor" here means member of a critical group, or Reasonably Maximally Exposed Individual (RMEI). The biosphere model thus allows the results of the geosphere transport model to be converted to annual dose in a manner that is consistent with performance assessment requirements specified [120].

The regulatory requirements as regards calculation of radiological impacts via groundwater release are prescriptive. That is to say, many of the assumptions to be made in the biosphere assessment have been defined by the regulator. As an illustration of the prescription, it is specified that it should demonstrate that features, events, and processes, which describe the biosphere, *"are consistent with present knowledge of conditions in the region, surrounding Yucca Mountain"* [120].

IV.4. SUMMARY COMMENTS

It may be noted that the level of prescription in national regulations and guidance varies. In some cases the assumptions made about environmental change and related biosphere changes are quite explicit. There are some variations in the timeframes for which quantitative assessment is required, but the use of more stylized approaches and complementary safety indicators for later times is a common trend. The more prescriptive examples naturally present scope for divergence from each other, and these in turn may reflect geographic and other locally specific factors. This reflects the comment in the MeSA report of the NEA [20], that, ''Greater differences exist between countries regarding the extent to which regulations allow simplified handling of the biosphere in the safety assessment", that is, compared with other aspects of the overall PA. However, taken altogether, there appears to be a trend towards taking account of change explicitly or at least being aware of the potential for change and the implications for post-closure safety within the overall safety case. This trend may reflect the increasing number of site specific analyses being undertaken.

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