BIOPROTA

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

Assessment of Processes in the Geosphere-Biosphere Sub-system in Post-closure Assessments of Radioactive Waste Repositories

Report of an International Workshop

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Version 2.0
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PREFACE

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

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

This report describes presentations and discussions held during an international workshop on Assessment of Processes in the Geosphere-Biosphere Sub-system in Post-closure Assessments of Radioactive Waste Repositories, held on 27 May 2015, hosted by CIEMAT in Madrid.

Version History

Version 1.0: Draft workshop report prepared by Karen Smith (RadEcol Consulting Ltd), Graham Smith (GMS Abingdon Ltd) and Mike Thorne (Mike Thorne and Associates Ltd) based on participant contributions, distributed for comment 21 August 2015.

Version 2.0: Final workshop report prepared, taking into account comment received on the version 1.0 report. Distributed 12 October 2015.

Executive Summary

The BIOPROTA forum has long recognised the relevance of having a clear understanding of possible processes for dilution and re-concentration as radionuclides transit between the traditional modelling domains, i.e. from the geosphere to the biosphere. Previous work organised within BIOPROTA has included a steady evolution in the development of understanding and modelling of relevant processes.

In particular, a methodology has recently been developed within the BIOPROTA programme, aimed at providing a structured approach to evaluating the geosphere-biosphere sub-system (GBS). There is now a need to consider how readily this approach can be applied, and how well it works, in assessments. These subjects were the focus of the one-day workshop on the 27 May 2015, organised through the BIORPOTA forum and hosted by CIEMAT in Madrid.

The key features of the GBS methodology were presented and discussed along with a range of recent modelling and assessment activities carried out within specific research and assessment programmes.

It was concluded that there is a range of mathematical models available, corresponding to the conceptual models developed. However, consideration has not been given as to how the conceptual models should then be addressed using these available models. This could be useful to consider in a relevant range of situations. A set of such situations has been identified by the IAEA MODARIA WG6, defined by:

- Mode of construction (e.g. excavated at surface, excavated at depth)
- Geological context (e.g. rock type)
- Hydrogeological context (e.g. saturated or unsaturated)
- Relation to coastline (e.g. inland, coastal, submerged)
- Potential to be influenced by effects of climate extremes (e.g. glaciation, periglaciation, desertification)

Such investigation, using site-generic and site-specific examples, could help to determine the circumstances in which detailed GBS modelling can be effective in improving confidence in assessment results, In particular, questions could be asked as to how GBS models can be simplified and/or relevant information abstracted for use in assessment models, whilst retaining complexity in those areas where simplification is not justified. The results could be used to guide site investigation and assessment programs.

It was noted that long-term averages tend to be applied in assessment models and these exclude, or represent through some form of averaging, processes that occur on shorter timescales. Consideration should therefore be given as to the appropriateness of different averages, including whether non-linear effects on processes, for example as a result of seasonality, should be taken into account.

It is suggested that further consideration should be given to river and stream interactions and corresponding radionuclide disposition and re-distribution, both as regards geomorphological processes and related radionuclide movement. For example, during flood events, radionuclide contamination of river banks and further afield could occur, depending upon the extent of the flooding. How long it then takes for those radionuclides to return to the river as a result of floodplain and bank erosion and other processes would be an interesting consideration in terms of radionuclide behaviour.

Sorption and de-sorption are critical processes in the assessment of radionuclide migration and accumulation. The use of Kd values can be challenged, particularly over long periods subject to environmental change. Further development and trial application of mechanistic modelling approaches for these processes could be carried out in order to incorporate variations in future conditions and to explore the implications for radionuclide sorption and desorption. The trial application could be made at specific sites that have already been characterised from a biosphere perspective. Examples suggested included the experimental catchment at Slapton Wood, Devon, UK, the Ravenglass Estuary, West Cumbria, UK and the Krycklan watershed in northern Sweden. Sufficient data may also be available for mires.

It is concluded that these issues could be addressed effectively in concert and on a shared cooperative basis as part of a review and update of the IAEA-BIOMASS-6 ‘Reference Biospheres’ methodology.

CONTENTS

1. INTRODUCTION

The BIOPROTA forum has long recognised the relevance of having a clear understanding of possible processes for dilution and re-concentration as radionuclides transit between the traditional modelling domains, i.e. from the geosphere to the biosphere. Previous work has included a steady evolution, as follows:

- BIOPROTA (2005): Modelling Processes in the Geosphere Biosphere Interface Zone. A report prepared within the international collaborative project BIOPROTA. Published on behalf of the BIOPROTA Steering Committee as Informes Técnicos CIEMAT 1062, ISSN: 1135-9420, CIEMAT, Spain.
- BIOPROTA (2005). Report of a Workshop to Evaluate Primary Features, Events and Processes Occurring in the Geosphere-Biosphere Interface Zone, 12-14 September 2005, Sant Cugat, Spain.
- BIOPROTA (2011). International workshop on the Functioning of the Geosphere-Biosphere Interface Zone, 6 - 8 September 2011, Louvain la Neuve, Belgium.
- BIOPROTA (2014). An Exploration of Approaches to Representing the Geosphere-Biosphere Interface in Assessment Models. Report prepared under the BIOPROTA international programme.

The last item represents a comprehensive framework for representing the geosphere-biosphere sub-system (GBS) in assessment models.

1.1 OBJECTIVES AND SCOPE OF THE WORKSHOP

The current workshop was intended to provide an opportunity for presentation and illustrated explanation of the methodology to the BIOPROTA community as a whole and for presentation of latest developments in related assessment work, with a view to preparing an overall review commentary and conclusions. Specific presentation and discussion topics included:

- Presentation of the developed GBS Methodology;
- Presentations of on-going work in modelling GBS processes;
- Analysis of the scope and need for further illustrative applications to near-surface and deeper facilities, in site-generic and site-specific contexts, and
- Development of a commentary on applications of the current GBS Methodology and the role of GBS modelling in a Reference Biospheres methodology.

The workshop was held in Madrid on 27 May 2015, hosted by CIEMAT.

1.2 TECHNICAL AND FINANCIAL SUPPORT

The workshop was attended by 25 participants from 10 countries, representing a range of operators, regulators, researchers and technical support organisations. Participants and their organisations are listed in Appendix A. Financial support for the workshop was provided by ANDRA, LLW Repository Ltd, NRPA, NUMO, SKB and POSIVA. The technical and financial support of participants and sponsoring organisations is gratefully acknowledged.

2. WORKSHOP PRESENTATIONS AND DISCUSSIONS

The references given in Section 1 recognise that the geosphere and biosphere need to be addressed coherently in assessments of the long-term impact of geological radioactive waste disposal facilities. The geosphere assessment provides possible releases to the biosphere, where the radiological impact is assumed to occur. The dilution of radionuclides in the near-surface environment, and the scope for accumulation and release in response to environmental change, are both important considerations. The geology, hydrogeology and geochemistry should be understood in order to evaluate the release and transport of radionuclides that could be discharged to the biosphere and how they behave in response to varying geochemical and other conditions.

A methodology has recently been developed within the BIOPROTA programme, aimed at providing a structured approach to evaluating the geosphere-biosphere sub-system (BIOPROTA, 2014). There is now a need to consider how readily this approach can be applied, and how well it works, in assessments. It is also timely to consider how the approach could be incorporated within a review and update of the IAEA-BIOMASS-6 ‘Reference Biospheres’ methodology. These subjects were the key focus of the one-day workshop.

The presentations by workshop participants and related discussions are summarised below.

2.1 A METHODOLOGY FOR REPRESENTING THE GEOSPHERE-BIOSPHERE INTERFACE IN ASSESSMENT MODELS

Mike Thorne presented an overview of the output of the 2014 BIOPROTA report on the methodology developed to address the geosphere-biosphere sub-system (GBS) in assessment models. The objectives of the project were:

- to develop scenarios for different types of geosphere-biosphere sub-system and to reduce these to a limited number that could be studied in detail in terms of their characteristic features, the events that could perturb them and the processes determining both their evolution and the transport of radionuclides within them and across their boundaries;
- to analyse the retained scenarios using suitable structured procedures (e.g. FEP analysis and Interaction Matrices) so as to develop conceptual models of the interfaces that were sufficiently detailed as to provide a well-defined basis for mathematical modelling of the various components and the processes affecting the characteristics of those components; and
- to identify and describe available approaches for mathematical modelling of the various components of the conceptual models and the processes relating those components.

The biosphere, as traditionally described in terms of soils, plants, surface waters etc., is very labile and can change considerably over time. Changes in the near-surface environment occur over much slower timescale whereas the deep geosphere is relatively constant, while the chemical compositions of groundwaters and their spatial distribution are subject to change over timescales of thousands of years. Therefore, whilst there is relatively long-term stability in the key features of the system, significant changes can be expected in relation to some aspects. Within assessments, the continuity of system components should therefore be recognised, but also the possibility for change. The interface between the geosphere and the biosphere is a region where radionuclide dilution and re-concentration processes can occur. It is less variable with time than the biosphere, but is likely to be significantly modified by landscape development over typical post-closure safety assessment timescales.

The project report deals comprehensively with the development of conceptual models of the GBS within selected scenarios and illustrates how the conceptual models can be defined in sufficient detail so that the mathematical representation follows naturally. Otherwise there can be a considerable jump from conceptual modelling to mathematical representation. Within the report, it is recognised that there is a range of mathematical models available, corresponding to these conceptual models, but specific consideration has not been given as to how the conceptual models should then be represented using these available models individually or in combination.

A conceptual model of the GBS is more than a description of processes; rather it must account for the geological area, an entity that exists both in space and time. Both climate development and landscape evolution are fundamental components that should be considered when building a conceptual model. Such features have proved to be very important in the SKB programme and, in the UK, incision modelling and coastal development are important considerations. As such, site assessment modelling within changing landscapes is often required, as a result of the long-term nature of assessments.

The assessment context does not usually define the GBS and, as such, a flow chart has been developed to support assessors in defining states of the GBS, transitions between those states and characteristics of both the states and transitions (Figure 2-1). This requires that thought is given to the mechanisms causing environmental change such as climate development, coastal processes etc., which may require global aspects to be propagated to the local level.

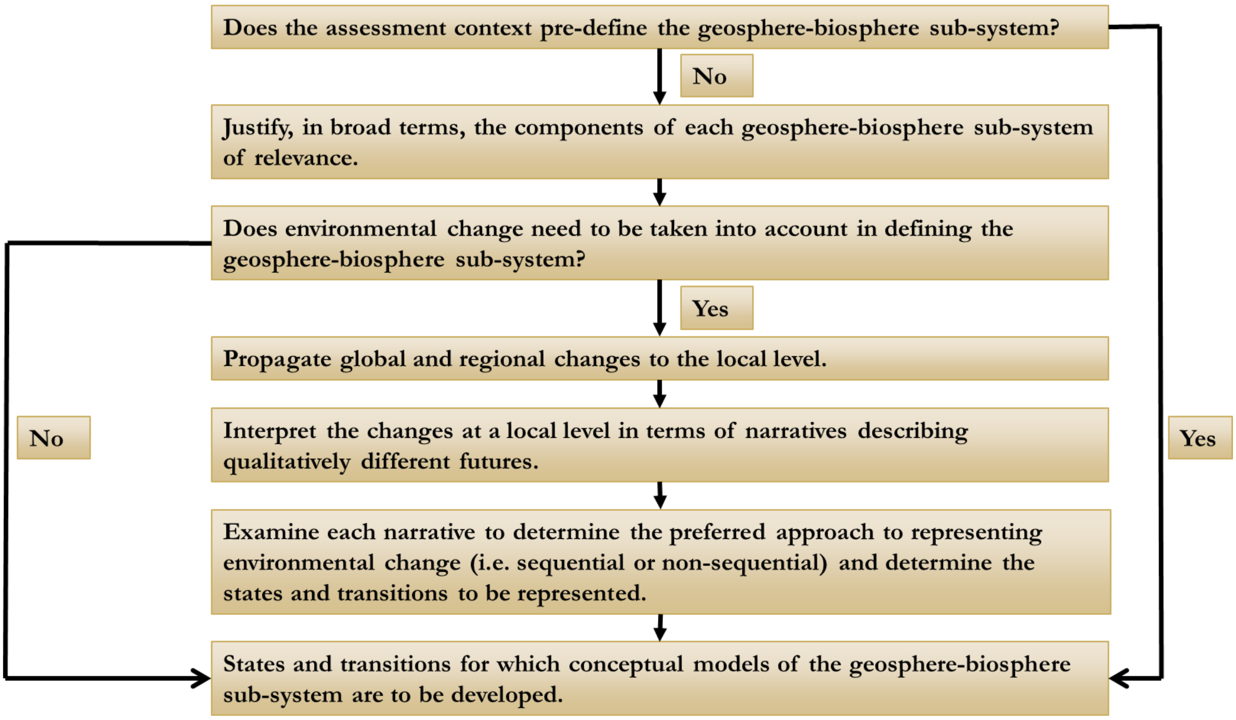


Figure 2-1. Process for defining the states and transitions of the GBS.

Climates, conditions and transitions have been considered previously within the BIOCLIM project, but the focus was mainly on states prior to, and after, transitions; the transitions themselves were only considered in terms of simple approximations. In terms of GBS components, the BIOPROTA [2014] report uses essentially the same classification as in the BIOMASS methodology, but moves toward specific consideration of the transitions between states.

There is a sequence of steps setting out how a system can be defined. A reasonable starting point is to consider climate changes and then landform development in the context of the changing climate. The hydrogeology will be dependent upon climate and changes in the landform, and, once the hydrogeology has been evaluated, it is then possible to consider hydrogeochemistry, which is determined both by patterns of groundwater flow and by water-rock interactions. This sequence of analyses can be undertaken first for individual states and, from this, detailed consideration can be given to the events and processes occurring during a transition from one state to another. The approach is outlined in Figure 2-2 and further guidance on approach is provided in the BIOPROTA [2014] report.

Select the state of the geosphere-biosphere sub-system immediately prior to the transition.

Select the state of the geosphere-biosphere sub-system immediately after the transition.

Match the detailed components of the geosphere-biosphere sub-system before and after the transition. This will include, one-to-one, one-to-several and several-to-one mappings.

Examine the transformations of the individual detailed components in turn to identify the events and processes that have given rise to the transition.

Identify any processes additional to those operating in the states immediately prior to and after the transition.

Define the transition of the geosphere-biosphere sub-system in terms of the detailed components existing before and after the transition, the mapping between those components over the transition and the complete set of events and processes operating within and between the components during the transition, including those giving rise to the transition.

Figure 2-2. Development of a conceptual model of a transition between two states of the GBS.

An illustration was presented for Lowland Britain on how to define states relating to two climate conditions; a warmer greenhouse climate and a cooler state some tens of thousands of years later. An interaction matrix has been developed where diagonal elements describe the properties of a particular element. Off-diagonal elements then provide detailed descriptions of how one element influences another. In order to allow detailed consideration of the influences between elements, it is necessary to distinguish features both spatially and conceptually. The diagonal elements are physical objects that encompass different features such as water bodies or specified strata and those features that physically occupy the same space but are different in kind should be separated such that, for example, soil solids and soil water are defined separately to allow absorption and desorption processes to be specifically represented within the interaction matrix.

Interaction matrices have become a common approach to demonstrating the comprehensiveness of system understanding. They can however be overwhelming in terms of complexity due to the number of influences between elements. Influence diagrams can be helpful in this regard. Alternatively, a tiered set of matrices can be developed to allow the unpacking of diagonal elements, but this is not a trivial exercise. The approach suggested in BIOPROTA (2014) is to use numbers within an interaction matrix that relate back to a table that provides more information on the processes and factors and variables that influence these. An illustrative table is presented in Figure 2-3. In then moving to a mathematical representation of processes, that representation should encompass all the processes within the interaction matrix off-diagonal elements as detailed in the complementary table. In total, this approach allows coherence to be evaluated whilst reducing complexity to a manageable level.

Once the interaction matrix and complementary table are completed, it is possible to build on the system by considering how the different diagonal elements can be impacted by human actions such as the drilling of a well. The system can then be collapsed, as appropriate, to focus on those elements that are of importance to a given scenario. It is necessary however to consider scenarios in broad terms to ensure that relevant aspects are identified and appropriately explained. As an example, well construction does not relate only to water extraction. Additional processes are relevant. For example, wells can provide the means by which oxygen can enter groundwaters and affect redox conditions.

Interactions	Description of the Interactions	Relevant Processes
1,7; 7,1; 2,8; 8,2; 3,9; 9,3; 4,10; 10,4; 5,11; 11,5	Interactions between a solid and its included water	Sorption/desorption; precipitation/dissolution; colloid formation and dissolution; advective and dispersive transport within the solid, including diffusion into intra-particle and inter-particle pore spaces. Relevant both to the composition of the solid and its included water and to the transport of contaminants within the solid/water system.
1,14; 2,14; 3,14; 4,14; 5,14	Effects of a solid on the composition of waters formed by the mixing of meteoric and aquifer waters	Rock-water interactions that modify the chemical composition of waters with different degrees of mixing. Mainly relevant to defining the composition of waters within which contaminant transport occurs.
5,13; 13,5	Interactions between the chalk aquifer and its included groundwater outside and within the GBI that together define the aquifer end-member water that is involved in the mixing process.	Rock water interactions throughout the aquifer, taking into account the composition of the meteoric water that recharges the aquifer at outcrop. Mainly relevant to defining the composition of waters within which contaminant transport occurs.
6,7; 7,6	Exchange of water between flowing streams and soils	Recharge and discharge through the stream banks and bed. Overbank flooding and return flow. Mainly relevant to contaminant transport.

Figure 2-3. Illustrative example of an interaction matrix complementary table.

There is a diversity of models available for exploring certain aspects of the GBS, such as models for water flow in permafrost systems and models for permafrost development. Geomorphological models continue to develop to allow erosion to be considered. Coupling between models is nonetheless a requirement for ensuring comprehensiveness of representation, but gives rise to substantial issues in ensuring consistency. Questions should therefore be asked as to how systems and processes can be simplified and/or relevant information extracted from one model as input to another whilst retaining complexity in those areas where simplification is not justified. Traceability and coherence should be maintained and mathematical justification documented for the models.

Radionuclide dilution occurs in the GBS as a result of meteoric water meeting deeper groundwater carrying radionuclides from the geosphere. Geochemical gradients can be large, affording scope for reconcentration. There can be competition between the dilution that occurs in greater water flows and processes leading to accumulation or desorption. Where the surface system and geosphere are considered separately, flow fields will need to be matched in 3D to ensure that these important processes are captured. These features are of course subject to change with time.

Climate and landscape development can be important considerations in long-term safety assessments, both affecting the GBS. The subject of how climate can inform assessments of landscape development is being considered by Working Group 6 of the IAEA MODARIA programme. Within this, consideration is being given as to how climate models of different complexity can be combined to inform on landscape change at a local level. Fossil-fuel emissions are related to atmospheric carbon dioxide concentrations that then relate to climate and, as such global climate models need to be integrated with carbon cycling models, which allows non-linear interactions to be considered and refined views of climate change to be developed. A climate emulator can be used in combination with multiple snapshot atmosphere-ocean general circulation model calculations to infer continuous changes under different time-dependent insolation, ice-sheet and atmospheric carbon dioxide concentration boundary conditions. The working group is also considering the extent to which quantitative models of landscape change in response to climate and climate change can be developed. This work is being underpinned by a significant RWM research programme.

Discussion

Different climate evolution stories can be constructed according to the carbon emissions scenario selected, which will in turn result in different narratives relating to geomorphology and landscape change. To address this, formal expert elicitation could be undertaken to gain a consensus opinion. However, if no consensus opinion can be obtained then it may be necessary to take forward a number of different stories to evaluate whether or not the differences have significant implications.

Site descriptive models are built up over several years and provide a comprehensive understanding of a site at the present day. The models are primarily based on site observations, but with some mathematical interpretation of those observations. Process models are then required to move from current to future landscapes and to represent the GBS over time. The processes occurring in the present day are included in the site-descriptive models and so, to some extent, data that will affect how things will change in the future are included.

The potential for re-concentration of radionuclides is not compatible with time-independent Kd sorption models. Hydrological and hydrogeological processes are required to be represented adequately in terms of changes in space and time such that processes leading to re-concentration can be accurately represented. However, long-term averages tend to be applied in assessment models and these exclude processes that occur on shorter timescales. Consideration should therefore be given as to the appropriateness of different averages, including whether non-linear effects, for example as a result of seasonality, should be taken into account. For example, if the water table over a year is considered, an average of water table depth over a year will not capture the upward and downward movement over seasons which may determine the net upward transport of radionuclides. As a result of such a simplification, the accumulation of radionuclides in soils as a result of changing redox conditions may be missed.

2.2 WHERE HAVE ALL THE RADIONUCLIDES GONE?

Ulrik Kautsky presented.

All Swedish radioactive waste disposal facilities are below ground so the GBS is of particular interest. SKB takes a holistic view of the GBS, rather than considering, for example, only a well scenario. The interface is itself a zone. Historically, hydraulic models tended to stop at a certain point below ground and so additional thought then needed to be given as to how the output from the hydraulic models is discharged to the surface. More recently, SKB models for the biosphere and geosphere fully overlap although communication between the modelling groups is vital to ensure consistency between input and output of the different models. In the latest assessment model for the operational and decommissioning waste disposal facility, SFR, the models were fully connected both in time and space; modelling approaches are therefore improving.

In the SKB approach, the landscape is divided into various landscape objects that are determined by, for example, the presence of a lake and its surrounding catchment area. These objects can change over time, for example the infilling of a lake leading to agricultural land or forest etc. The catchment area is always an important feature. For the SFR assessment, careful consideration was given to possible discharge zones. The geology, hydrology and surface geometry are all tightly connected and fracture zones are largely associated with lakes; hence, lakes are often the discharge zones. Once discharge zones had been identified, the number of people that could be sustained by each biosphere object was evaluated and the average annual effective dose to those people calculated.

The Swedish regulator, SSM, has provided a response to the modelling work performed by SKB. The view of SSM was that a discharge may not occur across an entire object however and, as such, the averaging approach taken by SKB may under-estimate doses. SKB has therefore been investigating the consequences, in terms of dose, of different discharge zone assumptions by considering wetland areas where discharges are most likely to occur or areas with the deepest soils that are suitable for agriculture. Radionuclide concentrations were found to vary by around one order of magnitude with the different assumptions, but the probability of occurrence also varies; discharge to soils suitable for agriculture is unlikely. A further constraint is whether small discharge areas can sustain people. As the size of area decreases, the need to obtain resources from outwith the area increases. When these constraints are taken into account, little difference in dose is observed.

The formation of taliks under cold climate conditions has also been considered. Various types of talik can form, including through, closed and open taliks (Figure 2-4).

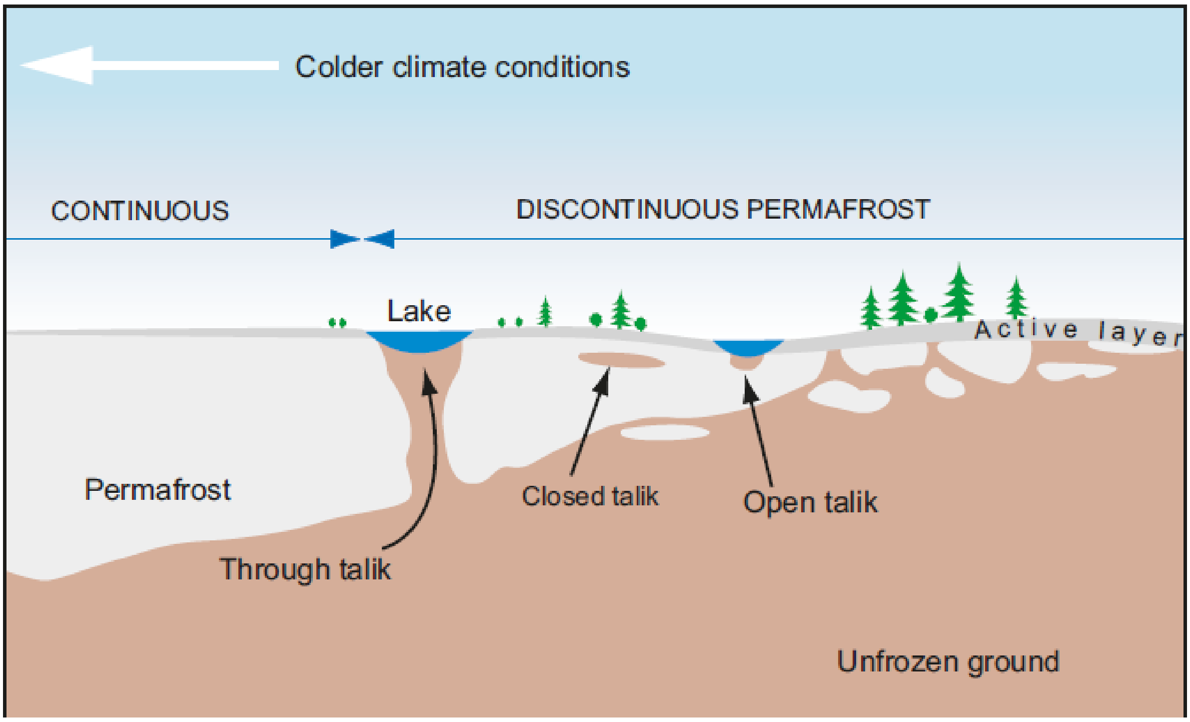


Figure 2-4. Illustration of the different types of taliks that can form under cold climate conditions.

It is also difficult to predict what areas of an object will be contaminated. If discharge areas are considered in detail, variation will be observed depending upon the models applied. For example, the ConnectFlow and Mike-SHE models vary in terms of predicted discharge areas with the former indicating near-river discharge points and the latter indicating within-river discharge points.

In addition to hydrology, the transport of elements needs to be considered and work is ongoing to look at element transport in relation to hydrology, geochemistry and object geometry and topography (see Section 2.3). Initial results demonstrate the variability of sorption over time and space in relation to variations in geochemistry.

In summary, catchment area has been found to be a more important feature than object size in assessments and uncertainty remains in the exact discharge locations within specific biosphere objects. The discharge of radionuclides directly into running waters is an important consideration for SKB.

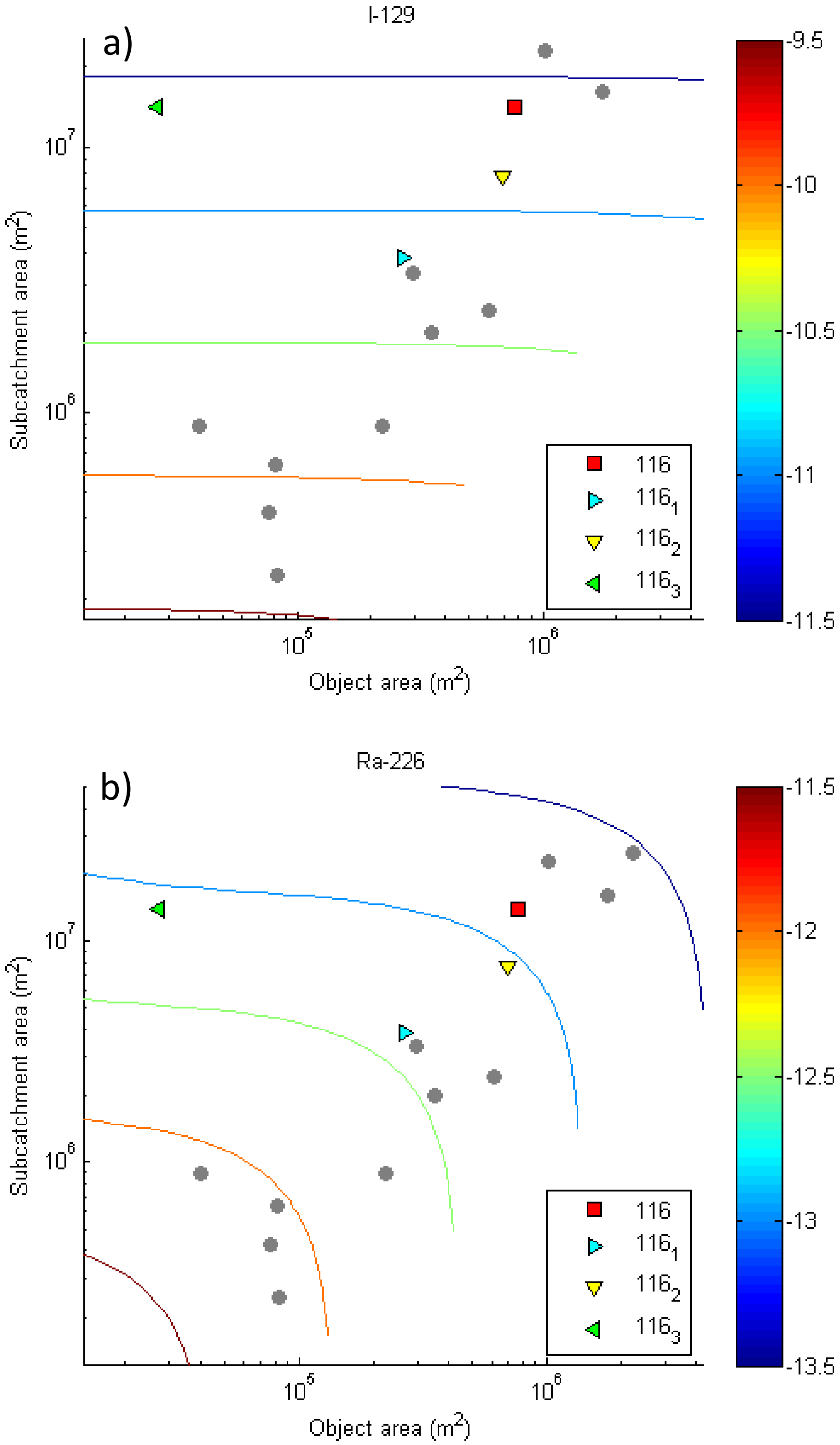


Figure 2-5. **Effect of sub-catchment and object areas on activity concentrations of a) I-129 and b) Ra-226.**

Discussion

The issue of river and stream interactions has not yet been fully addressed as yet and it is possible to get the impression that, by refining the model, discharge lines could be pushed into streams. However, over the course of a year the stream flow will vary considerably, with the stream, or individual reaches of it, potentially changing from recharge to discharge conditions with season. In the UK, if a stream channel is matched to the existing flow domain (not all streams are so matched, some exhibit underfit characteristics in floodplains formed in a past, hydrologically more active situation) then flooding events could occur and, over the course of a few years, stream banks could be contaminated. Whether or not the effect is averaged out as the landscape changes could be argued. Consideration therefore needs to be given as to whether assessment models should be so detailed as to represent such events and processes or whether a description of the events and processes, and a representation through effective parameters, is sufficient for assessment purposes. In Sweden, the situation is different to that in the UK. Rainfall tends to percolate through soils to groundwater and it is the groundwater that then feeds the streams. Where there is a large catchment area, more meteoric water will recharge groundwater which in turns increases the flux of groundwater, and the transport of radionuclides within that groundwater, to the surface. Seasonality and catchment areas are therefore important and there is a need to consider how to integrate seasonality with the timescale of models, i.e. to consider the appropriate averaging of seasonal variations as input to long-term models.

A further complexity in assessments is that it is not possible to predict which canisters in a deep repository for spent fuel will fail and the positioning of these. The position of a failing canister will have a potentially large impact on the discharge zone.

2.3 TOWARDS A REACTIVE TRANSPORT MODEL OF THE BIOSPHERE IN BOREAL ENVIRONMENTS

Elena Abarca presented a feasibility model integration exercise aimed at evaluating the use of iCP (COMSOL-Phreeqc interface) to simulate mechanistic radionuclide reactive transport processes under realistic (3D heterogeneous) hydrological conditions. The exercise was undertaken for SKB, focussed on the Forsmark region.

Radionuclide sorption is commonly simulated using a lumped approach where retention processes are represented by a single parameter, the distribution coefficient (Kd) that relates the radionuclide concentration retained in the solid phase to its aqueous concentration. This approach relies on two key assumptions: 1) Kd depends only on soil properties and 2) Kd is constant in time. In reality, however, sorption processes vary both spatially and temporally according to a variety of factors, including redox conditions. The reactive transport model, implemented in iCP is intended to take account of the actual geochemical conditions that control sorption and desorption, in an ‘intelligent Kd’ approach.

The models considered included a regional hydrology model, a surface hydrology model (Mike SHE) and a sedimentary GIS model. SKB had also been developing complex geochemistry models using PHREEQC that was also employed. Each of these models was integrated into the iCP tool.

The GBS is represented geometrically in 3D, illustrated below with vertical exaggeration. The approach allows groundwater flow to be conceptualised in 3 dimensions, according to flow-system assumptions (Figure 2-6). Within the bedrock, water flow is largely vertical as illustrated for a deep-flow system (lower right figure), but becomes horizontal on reaching the regolith. In a shallow-flow system, flow is largely horizontal, with water being derived from the surface system (upper right figure). Of the water discharging to a surface lake object, 90% is due to recharge and the remaining 10% is from deep groundwater. As such, there is a large dilution of groundwater in surface lakes.

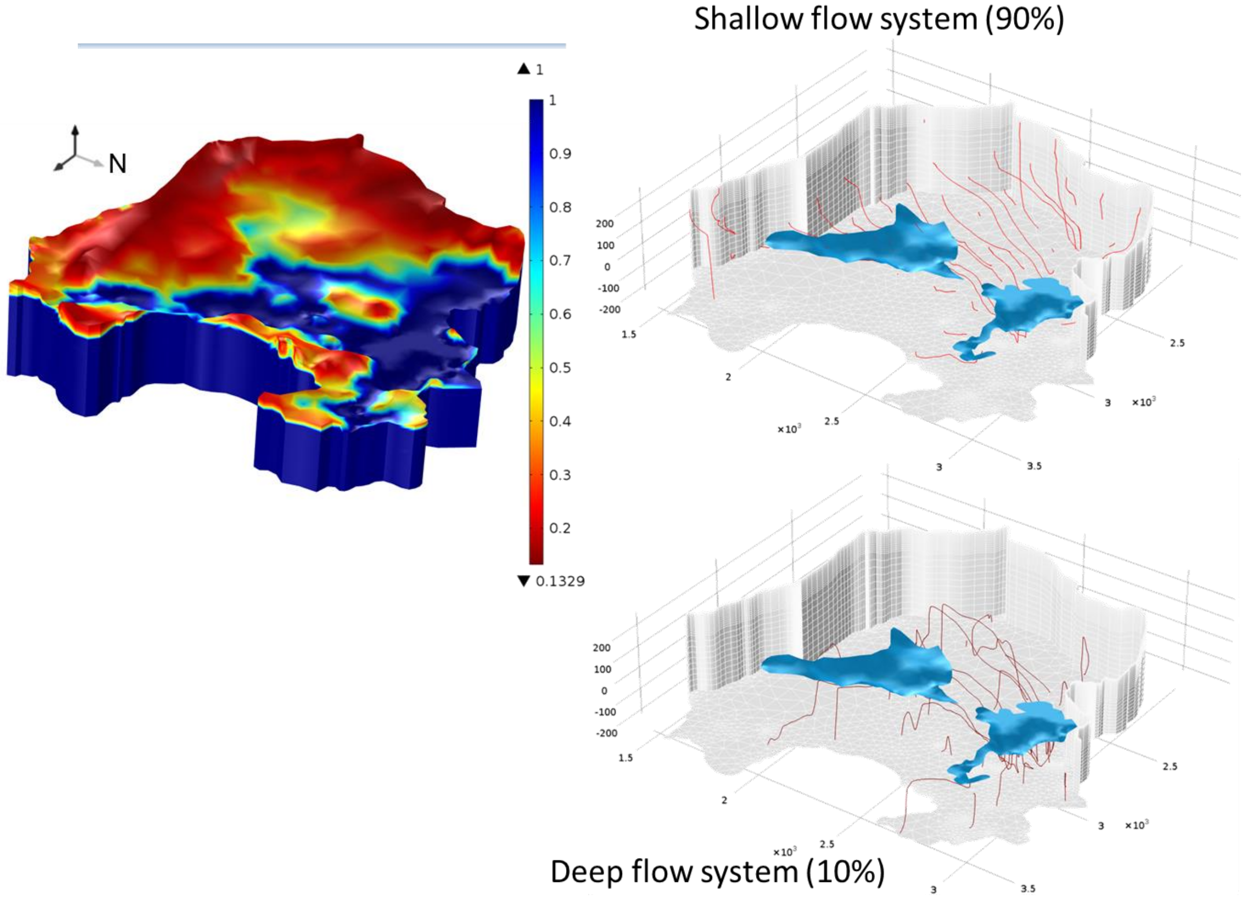


Figure 2-6. iCP representation of a groundwater flow system.

Four radionuclides have been considered. They were selected to illustrate the effects of different dominant retention processes (Table 2-1). Uranium is only sorbed in till due to the redox conditions present in clay.

Geochemical boundary conditions were extracted from SKB publication R-08-107 (Complementary modelling of radionuclide retention in the near-surface system at Forsmark) and a prescribed concentration of each radionuclide in deep groundwater was set as the radionuclide source and was not considered to be homogenous across the bottom plane. The plume of radionuclides in groundwater moves vertically leading to an increase in concentration of absorbed radionuclides in low topographic areas. The majority of radionuclide accumulation occurs at the borders of lakes rather than in the centre that would represent the local topographic low point.

Table 2-1. Radionuclides and their retention processes.

Radionuclide	Retention processes
Sr-90	Sorption in planar sites Precipitation of Strontianite
Cs-137	Sorption in planar sites Sorption in type II sites Sorption in X_{FES} sites
U-235	Sorption on $Fe(OH)_3$ surface (strong and weak sites) (only in the Till) Precipitation as Uraninite (only in the Clay)
Ra	Precipitation as Radiobarite

The iCP fully mechanistic reactive transport model has been used to derive Kd values, based on concentrations in solution and that sorbed according to different processes and, for example, changes in water flow. This approach has allowed Kd to be derived as a function of time and space. Two types of equivalent Kd calculations have been tested:

i) Spatial distribution of Kd at the end of the RT simulation

$$K_{d,RN}(x,y,z) = \frac{\theta_l(x,y,z)}{\rho_b} \frac{C_{RN,retained}(x,y,z)}{C_{RN,dissolved}(x,y,z)}$$

ii) (ii) Time dependent Kd function for till and clay

$$K_{d,RN,\Omega}(t) = \frac{1}{V_\Omega}\left(\int_\Omega \frac{\theta_l(x,y,z)}{\rho_b} \frac{C_{RN,retained}(x,y,z)}{C_{RN,dissolved}(x,y,z)}\right)(t)$$

where $C_{RN,retained}$ is the concentration of a retained radionuclide (RN); $C_{RN,dissolved}$ is the concentration of a dissolved RN; θ_l is the volumetric liquid content, ρ_b is the bulk soil density; Ω represents a material (till or clay); and V_Ω is the volume of material Ω. Kd values for the four radionuclides at an elevation of 3m are illustrated in Figure 2-7, which illustrates the spatially varying Kd values obtained. Temporal variations in Kd were also observed (Figure 2-8) for clay and till.

The derived Kd values have been compared against literature values, both in terms of arithmetic and geometric means. For some radionuclides (e.g. U-235) results were within an order of magnitude, but a greater difference was observed for others, with radium showing the greatest divergence (see Figure 2-9). The complex Kd approach takes into account sorption and precipitation, which may account for some of the observed differences. Furthermore, the literature values may relate to high sulphate systems and relate to a single site.

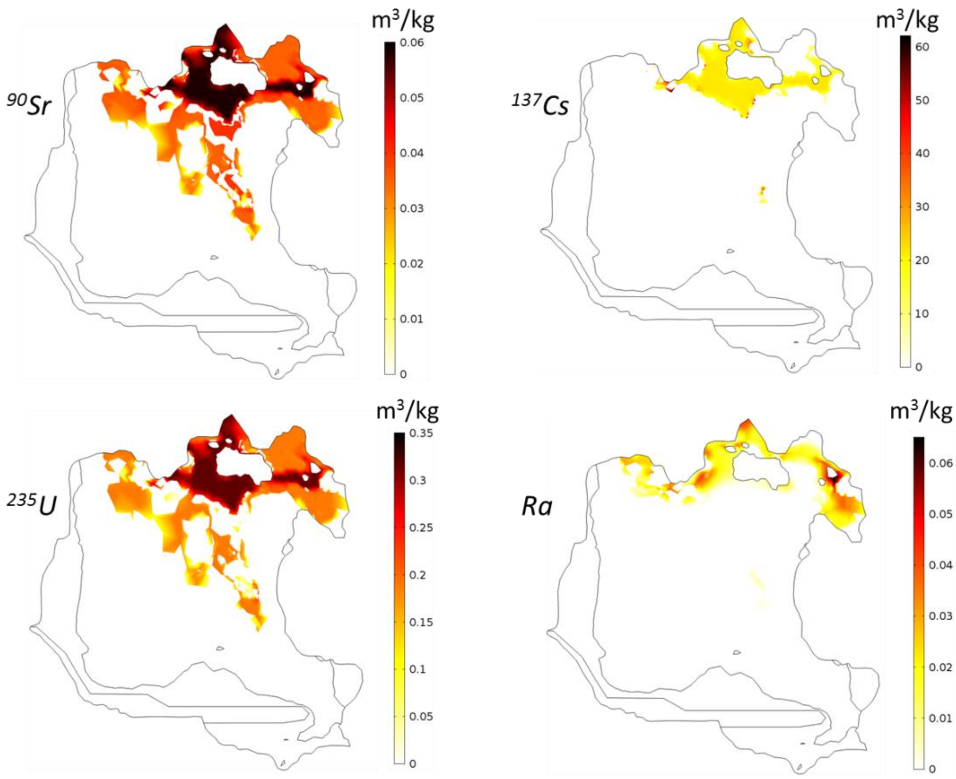


Figure 2-7. Kd field at the end of the iCP simulation for the radionuclides Sr-90, Cs-137, and U-235, and Ra.

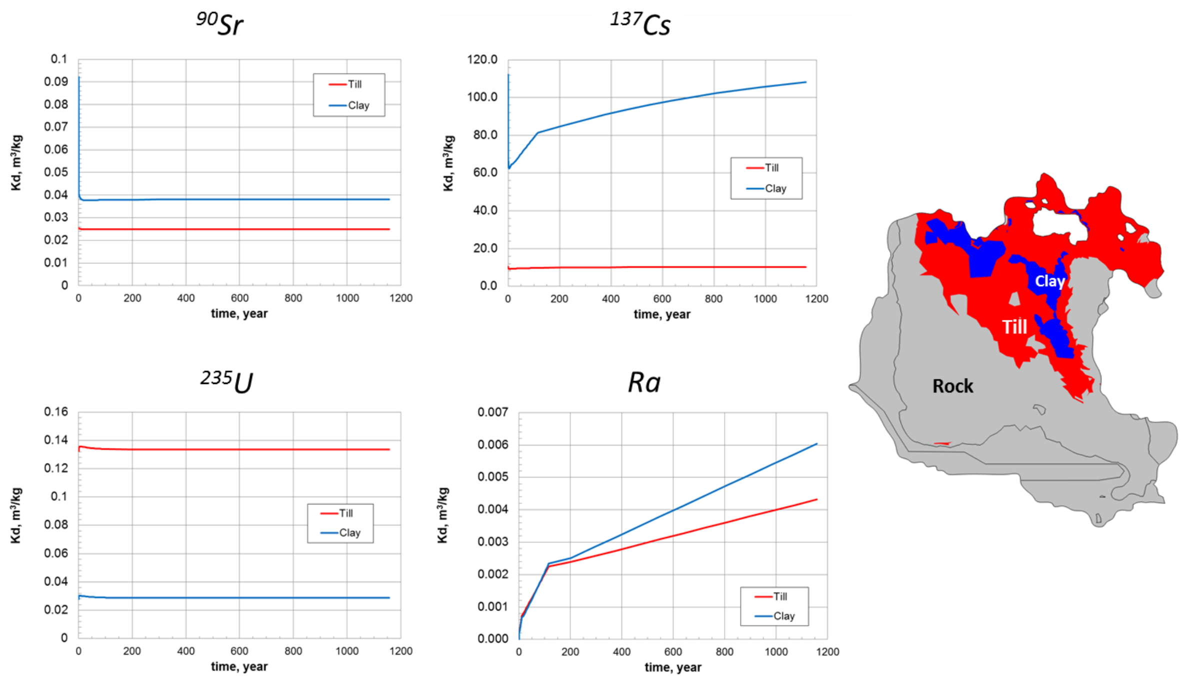
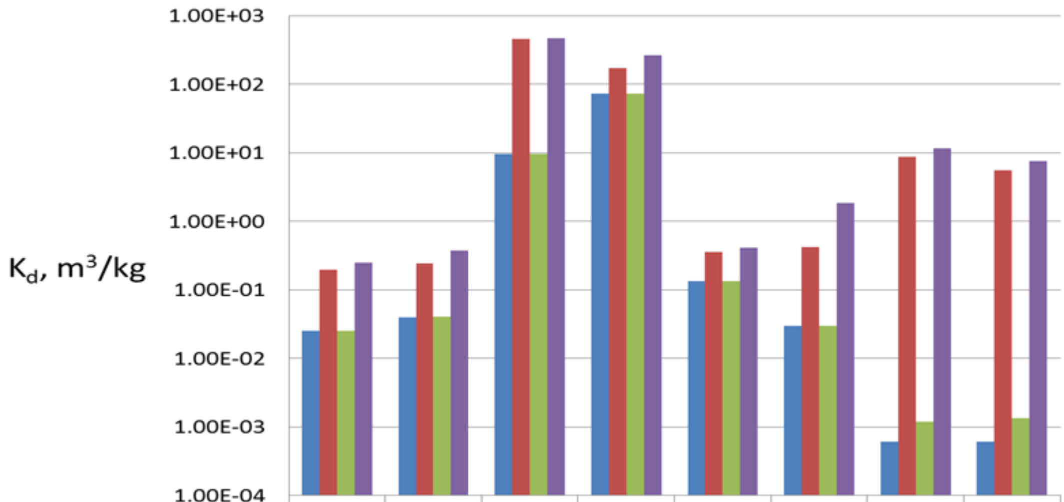


Figure 2-8. iCP derived time dependent Kd values for clay and till domains at an elevation of 3m.



	90Sr, Till	90Sr, Clay	137Cs, Till	137Cs, clay	235U, Till	235U, Clay	226Ra, Till	226Ra, Clay
GM this study	2.51E-02	4.01E-02	9.60	72.73	1.34E-01	2.95E-02	6.11E-04	6.14E-04
GM Shepperd et al. (2011)	0.1985	0.2453	461.5	172.4	0.3557	0.4239	8.738	5.533
AM this study	2.51E-02	4.05E-02	9.61	73.87	1.34E-01	2.95E-02	1.18E-03	1.33E-03
AM Shepperd et al. (2011)	0.2493	0.3753	475.0	265.1	0.409	1.868	11.72	7.500

Figure 2-9. Comparison of iCP-derived Kd values (AM and GM) and literature data for clay and till.

The different Kd approaches have also been applied to derive maximum concentrations of radionuclides at breakthrough points in a lake object. The resultant breakthrough curves did not display good agreement between the models. It has, nonetheless, been concluded that the equivalent Kd-based model could be improved to better fit the mechanistic reactive transport model.

A new project is now starting to validate the iCP tools through comparison of results against field data and to set up generic process-based models that can be applied to other catchments in the Laxemar and Forsmark regions of Sweden. The Krycklan watershed in northern Sweden has been subject to thorough investigation of the key processes controlling biochemical cycling of metals in the boreal landscape. A hillslope profile and a 2D riparian zone transect are available for the site. Data are also available on soil composition and detailed sampling campaigns have been carried out to measure both metals and radionuclides. The available data for the site has led to its selection as the basis for model-data comparison.

Discussion

Mechanistic model approach to Kd allows future variations in conditions and their implications for radionuclide sorption to be evaluated, whereas the simple Kd model is more a back-fitting approach.

Additional sites that have been well characterised for which models are available already include the experimental catchment at Slapton Wood, Devon, UK and the Ravenglass Estuary, West Cumbria, UK. Slapton Wood in particular presents a good opportunity for model validation, with full hydrological characterisation having been undertaken along with hydrogeochemical investigations over several decades. Sufficient data may also be available for mires; a literature study is being proposed within BIOPROTA that could provide the basis for such data to be identified.

In relation to river catchments, it was noted that, during flood events, radionuclide contamination of river banks and further afield could occur, depending upon the extent of the flooding. How long it would then take for those radionuclides to return to the river as a result of floodplain development, bank erosion and other processes would be an interesting issue to address.

2.4 NEW ESTIMATES OF IRRIGATION AND DRAINAGE RATES FOR THE RADIOLOGICAL IMPACT ASSESSMENT CODE BIOSPHERE

Talal Almahayni presented.

The BIOSPHERE assessment model (Figure 2-9) is comprised of a contaminated aquifer with a well that is used for the abstraction of water for irrigation of food crops and drinking water for people and cattle.

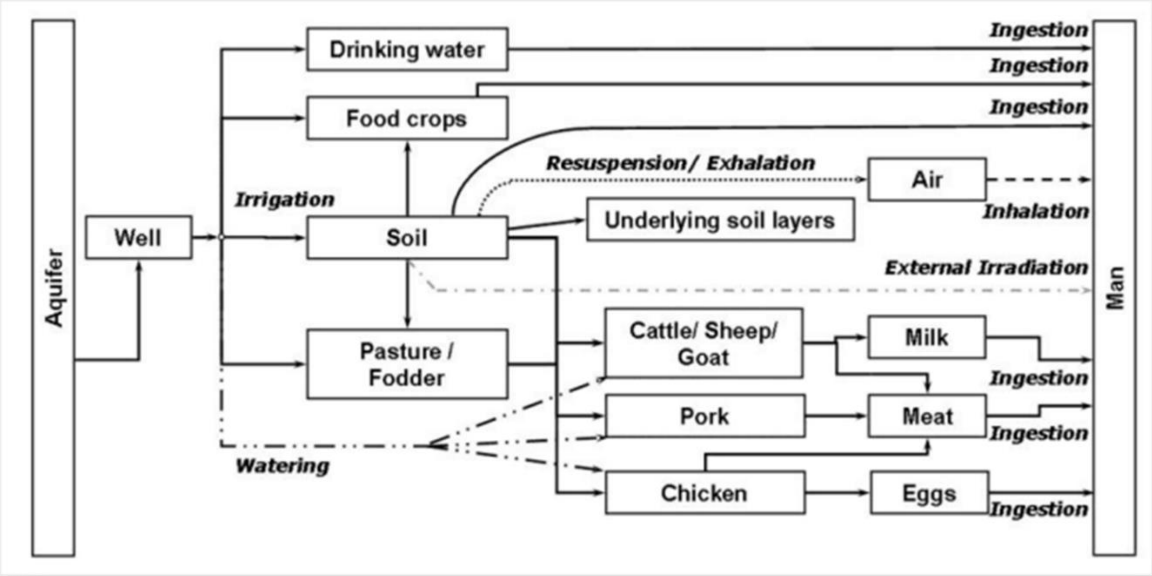


Figure 2-9. The BIOSPHERE conceptual model.

Irrigation and drainage are important inter-connected parameters for evaluating the transfer of radionuclides to plants. Uptake of radionuclides by plants from irrigation water may be via foliar interception or by root uptake. Drainage can reduce the inventory of radionuclides in soils through leaching as water percolates through soils. Both irrigation and drainage will be affected by the mass balance of water in the rooting zone, which will in turn be affected by changes in climate. The effect of climate change on dose is therefore being investigated.

The climate in Belgium is currently temperate. In around 160,000 years from now a subtropical climate is expected to occur, followed by a subarctic climate from around 170-180k years After Present. These climates are based on a sequence constructed from data from northern France and eastern England. Analogues have been sought for the different climates to see respective change in irrigation and drainage. Since irrigation is the primary process for transferring radionuclides from groundwater to food crops, the implications of the different climate states on irrigation rates is of particular interest. A review of what others have considered in assessment codes has been undertaken and data from different countries with climates analogous to those of interest (e.g. Spain and Sweden) have been identified from databases, published surveys and research papers. The databases identified tended not give irrigation rates per crop, but rather data on the total amount of irrigation and the area irrigated. Information on soil type also tended to be lacking. A further concern is that irrigation rate may need to be considered in terms of season and annual averages may not therefore be so appropriate. Some inconsistencies were also identified in the data presented between different databases. For example, the AQUASTAT and Eurostat databases gave irrigation rates of 76 and 176 mm/y, respectively, for Sweden.

An alternative approach, and one that is a standard procedure for irrigation scheduling, is to calculate the irrigation water requirement of crops. AQUACROP is a computer code that is extensively used for this purpose and was therefore employed to estimate the irrigation and drainage rates for typical Belgian crops under the different climate regimes. The AQUACROP model applies the concept of water productivity, which is the above ground biomass produced per unit land area per unit of water transpired. The code is user-friendly and has been applied for a wide range of applications.

AQUACROP requires a range of weather parameter variables, including precipitation, air temperature, reference evapotranspiration and mean annual carbon dioxide concentration. Three analogue stations were selected as sources of weather parameter data to represent the different climate regimes with data being obtained from the European Climate Assessment Dataset for the time series 1979 to 1988. One issue encountered however was that humidity data, required to calculate the reference evapotranspiration, were often lacking.

In addition to weather parameters, crop and soil parameters are also required. Plant physiology is complex, but the model documentation provides some default values for crops under some climate regimes. Soil parameters required include physical characteristics such as horizon depth and texture, organic matter content etc. as well as hydraulic characteristics such as field capacity. A study undertaken in Belgium has provided a range of relevant data for soils across the country and this was used to calibrate the model for crops (potato and wheat) in the Flanders region. The data, presented within the Belgian Soil Information System, provided suitable parameters for physical characteristics of soils, but not the hydraulic properties. These were therefore estimated on the basis of the physical characteristics of the soil.

Results of reference evapotranspiration and precipitation under the different climates are presented in Figure 2-10. Irrigation rates for different crops were also simulated; once water in the root zone falls below field capacity, the code brings this back up to field capacity by assuming irrigation takes place. A greater irrigation requirement is always associated with the sub-tropical climate with a range of 61mm to 570mm being calculated for cabbage cultivated under the different climates. The soil type and crop type also affect irrigation requirements, but to a much lesser extent.

Drainage is also calculated by the code and shows a greater variability as compared with irrigation; total drainage ranged from 20 to 800 mm/y. This is largely due to drainage occurring throughout the year whereas irrigation is limited to the growing season. Drainage under a temperate climate was the highest, with the lowest drainage being associated with a sub-tropical climate.

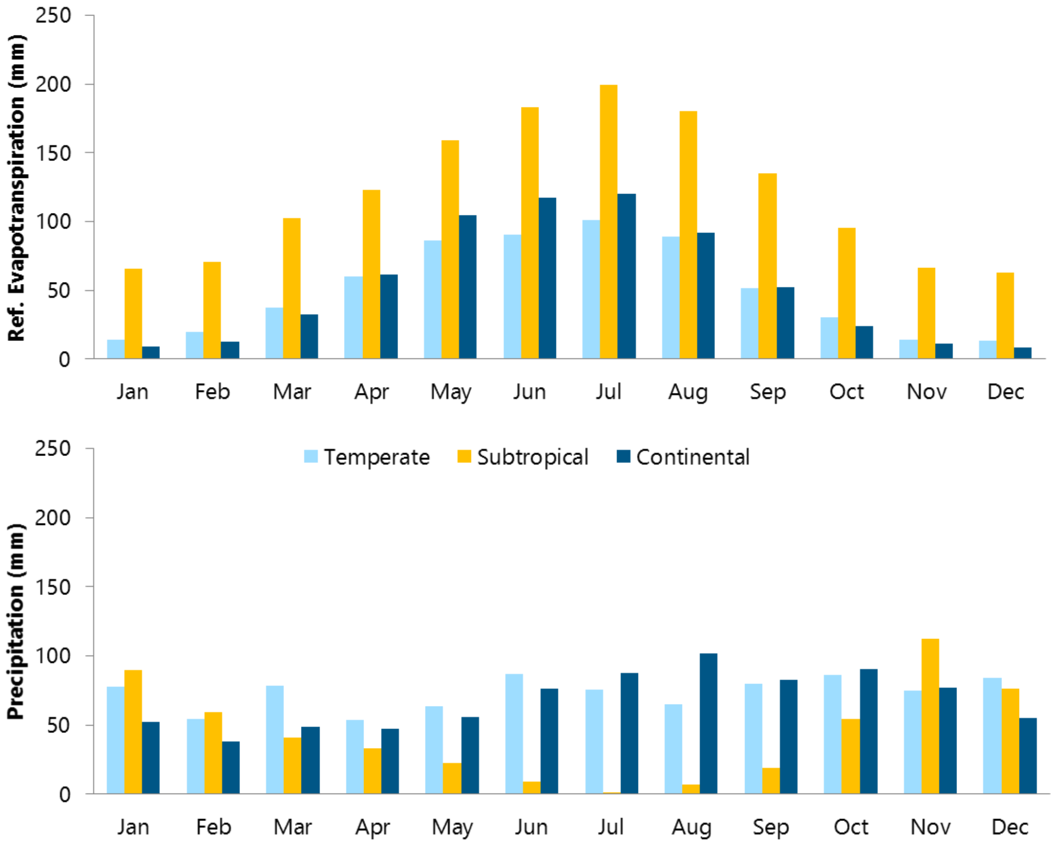


Figure 2-10. Assessment results for reference evapotranspiration (upper figure) and precipitation (lower figure) under temperate, subtropical and continental (cooler) climate conditions.

Results have been validated against published data (Table 2-2). Simulated results for cabbage were very close to published data and for green bean the simulated data are close to the upper range of published data for a sub-tropical climate. Variations between simulated and published data can, in part, be explained by literature data focussing to a large extent on water saving whereas the model does not factor in water saving requirements.

In addition to annual values for irrigation and drainage, the model allows time series data to be simulated as input to high resolution models that require sub-annual time steps.

Of the key variables considered, climate had the greatest impact on both irrigation and drainage. For the scenarios simulated, the transition from present-day temperate climate to a warmer/subtropical state increased the crop irrigation requirement up to 300%. This increase in irrigation requirement was associated with a decrease in drainage.

Table 2-2. Comparison of irrigation (mm/y) simulated with AQUACROP against values reported in the literature.

Crop	Climate	Published	Simulated	Reference
Cabbage	Semi-arid	460-570	441-568	Wellens et al. (2013) Sahin et al. (2009)
Green bean	Temperate	20-408	98-237	Vanuytrecht (2013), Kuşçu et al. (2009)
	Subtropical	157-338	306-337	Sezen et al. (2005), Bonachela et al. (2006)
Potato	Subtropical	4-477	291-423	Ferreira and Carr (2002)
	Temperate	82-285	120-372	Bodemkundige Dienst van België (2014); Ahmadi et al. (2011); Bodemkundige Dienst van België (2008); Shahnazari et al. (2008)
Wheat	Subtropical	95-396	121-413	Cossani et al. (2012); Albrizio et al. (2010); Sezen and Yazar (2006); Oweis et al. (2000)

Discussion

A similar range of issues was considered in the IAEA EMRAS 2 programme (WG3) with variation in irrigation rates under different climate states being examined. The data from this study could provide the basis for a good cross-validation exercise. The WG3 report also provides an overview of international and national guidance on addressing climate change in post-disposal safety assessments.

Irrigation schedules are aimed at maintaining soil moisture levels above the moisture deficit. However, optimal crop growing conditions are often associated with soil moisture levels below field capacity since this can help prevent disease, or indeed, there simply may be a shortage of water.

2.5 SOIL AND SEDIMENTS – GEOSPHERE AND BIOSPHERE

Anne-Maj Lahdenperä presented.

In Finland, LLW and ILW are disposed at a depth of around 100 m at the sites of the Olkiluoto and Loviisa nuclear power plants. HLW is currently stored in pools in facilities near the nuclear power plant reactors prior to geological disposal. Posiva is the organisation responsible for the management and disposal of spent nuclear fuel.

Olkiluoto Island has been selected as the site for geological disposal of spent nuclear fuel. The island is subject to post-glacial land uplift at a rate of around 6 mm/y. As such, the present day sediments around the island will, over time, become the future soils on the island. The sediments therefore govern vegetation succession over time and biotope classification is driven by the sediment and soil types, but taking into account additional features such as photosynthetic radiation availability. The biotope classification approach taken in the BSA-2012 assessment is illustrated in Table 2-3.

Table 2-3. Soil and sediment types as the basis for biotope classification in the BSA-2012 assessment.

<table>
<tr><th rowspan="2">Soil/sediment type</th><th colspan="3">Terrestrial biotopes</th><th colspan="6">Aquatic biotopes (sea/lake/river)</th></tr>
<tr><th>Forests and mires</th><th>Crop types *</th><th>Pasture *</th><th></th><th colspan="3">Well-lit bottom</th><th>Dark bottom</th><th></th></tr>
<tr><td>Rocky soil</td><td>Rock forest</td><td rowspan="3">ø</td><td rowspan="3">ø</td><td rowspan="6">Reed bed</td><td>Photic hard bottom (lake/sea)</td><td rowspan="6">Open river</td><td rowspan="6">Shaded river</td><td rowspan="3">Aphotic hard bottom (lake/sea)</td><td rowspan="6">Open sea</td></tr>
<tr><td>Coarse-grained mineral soil</td><td rowspan="3">Heath forest</td><td rowspan="5">Photic soft bottom (lake/sea)</td></tr>
<tr><td>Medium-grained mineral soil</td></tr>
<tr><td>Fine-grained mineral soil</td><td>(x)</td><td rowspan="4">x</td><td rowspan="3">Aphotic soft bottom (lake/sea)</td></tr>
<tr><td>Clay</td><td rowspan="2">Grove</td><td rowspan="3">x</td></tr>
<tr><td>Gyttja</td></tr>
<tr><td>Peat</td><td>Mire</td><td>–</td><td colspan="3">–</td><td>–</td><td>–</td></tr>
</table>

The properties of the overburden determine to a large extent the type of vegetation that will grow and, from this, the available habitats for fauna that could be expected to be present in the long-term. The different types of overburden of relevance to Finland include clay, formed in sheltered bay environments; sand and gravel that are formed, following glaciation, by running waters; humus which forms from the decomposition of organic matter and till, which is glaciated sediment of a mix of grain sizes.

A schematic of the soil layers has been developed based on excavations at the Olkiluoto site. This schematic has been used to derive biosphere assessment model compartments (Figure 2-11).

Soil types, defined by current sediments in the coastal environment, are used to determine future croplands and the type of crops that could be cultivated. In addition to terrestrial biotopes, lakes and mires will also develop as land uplift continues. A gradual progression from semi-enclosed bays through to lakes, and subsequent infilling leading to peat bog formation occurs over time. The biotopes within lakes (and also coastal areas) are based on the fertility of bottom sediments. The sediments also determine attachment possibilities for plants and habitats for bottom-dwelling fauna with factors such as light conditions within the water column also being important.

A third of the surface area of Finland is covered by peatland (mires). Peatlands are biological storage areas and are important to the overall water balance and associated radionuclide transport. A peat growth model has been used to identify mire areas. Where the groundwater table is close enough to the ground surface, peat-forming vegetation prevails and peat accumulation begins.

The current sea sediments are therefore key to evaluating the future development of different biotopes.

Discussion

Whilst soil profiles for the current time are important for evaluating how soils on newly emerged land areas will form, soil horizons will continue to evolve over long timescales. It would therefore be useful to study old soil horizons in a Reference Area and to compare them against those that have more recently formed to inform on the long-term evolution of the soils.

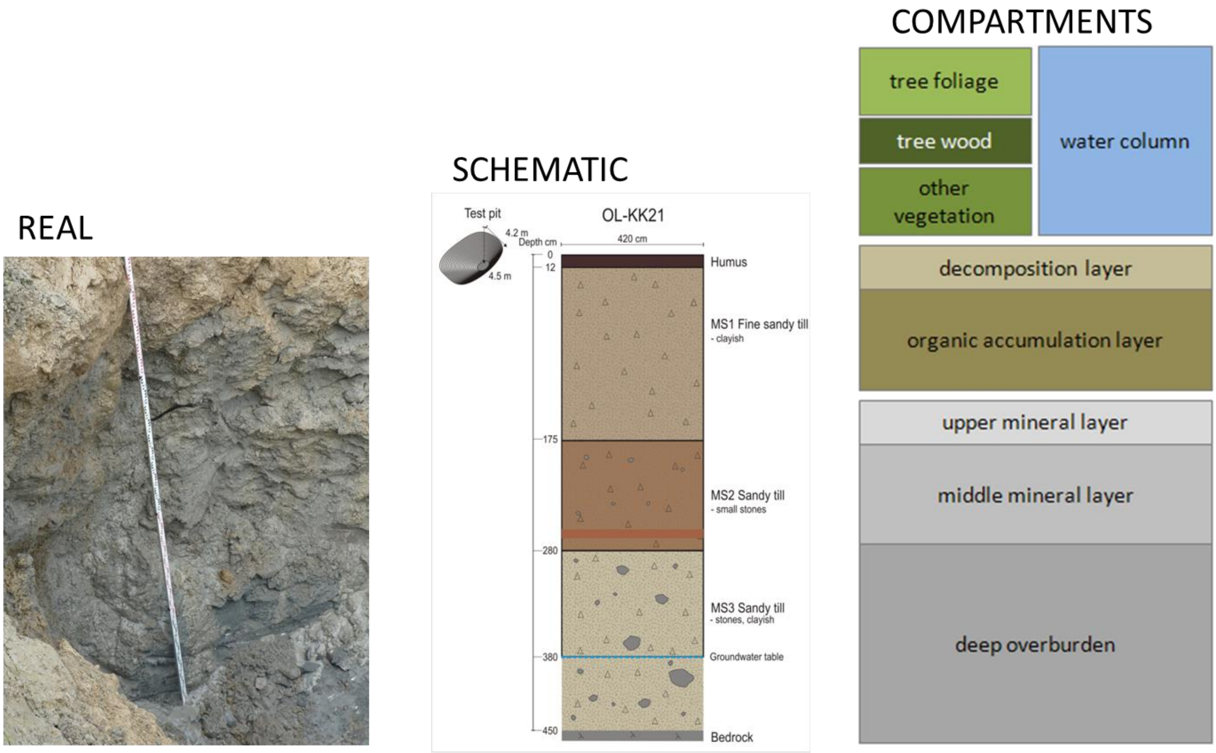


Figure 2-11. Soils and their representation in the biosphere assessment BSA-2012.

3. NEXT STEPS IN ADDRESSING THE GEOSPHERE-BIOSPHERE SUB-SYSTEM IN ASSESSMENT MODELS

There is a range of mathematical models available, corresponding to the conceptual models developed. However, consideration has not been given as to how the conceptual models should then be addressed using these available models. This could be useful to consider in a relevant range of situations. A set of such situations has been identified by the IAEA MODARIA WG6, defined by:

- Mode of construction (e.g. excavated at surface, excavated at depth)
- Geological context (e.g. rock type)
- Hydrological context (e.g. saturated or unsaturated)
- Relation to coastline (e.g. inland, coastal, submerged)
- Potential to be influenced by effects of climate extremes (e.g. glaciation, periglaciation, desertification)

Such investigation, using site-generic and site-specific examples, could help to determine the circumstances in which detailed GBS modelling can be effective in improving confidence in assessment results. In particular, questions could be asked as to how GBS models can be simplified and/or relevant information abstracted for use in assessment models, whilst retaining complexity in those areas where simplification is not justified. The results could be used to guide site investigation and assessment programmes.

It was noted that long-term averages tend to be applied in assessment models and these exclude, or represent through effective, time-averaged parameter values, processes that occur on shorter timescales. Consideration should therefore be given as to the appropriateness of different averages, including whether non-linearities in the effects of processes, for example as a result of seasonality, should be taken into account.

It is suggested that further consideration should be given to river and stream interactions and corresponding radionuclide disposition and re-distribution, both as regards geomorphological processes and related radionuclide movement. For example, during flood events, radionuclide contamination of river banks and further afield could occur, depending upon the extent of the flooding. How long it then takes for those radionuclides to return to the river as a result of floodplain development, bank erosion and other processes would be an interesting issue to address.

Sorption and de-sorption are critical processes in the assessment of radionuclide migration and accumulation. The use of Kd values can be challenged, particularly over long periods subject to environmental change. Further development and trial application of mechanistic modelling approaches for these processes could be carried out in order to incorporate variations in future conditions and to explore the implications for radionuclide sorption and desorption. The trial application could be made at specific sites which have already been characterised from a biosphere perspective, Examples suggested included the research catchment at Slapton Wood, Devon, UK, the Ravenglass Estuary, West Cumbria, UK and the Krycklan watershed in northern Sweden. Sufficient data may also be available for mires.

It is concluded that these issues could be addressed effectively in concert and on a shared cooperative basis as part of a review and update of the IAEA-BIOMASS-6 ‘Reference Biospheres’ methodology.

APPENDIX A. LIST OF PARTICIPANTS

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