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Technical Note

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Review of Landscape Models used in SR-Site

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SSM perspektiv

Bakgrund

Strålsäkerhetsmyndigheten (SSM) granskar Svensk Kärnbränslehantering AB:s (SKB) ansökningar enligt lagen (1984:3) om kärnteknisk verksamhet om uppförande, innehav och drift av ett slutförvar för använt kärnbränsle och av en inkapslingsanläggning. Som en del i granskningen ger SSM konsulter uppdrag för att inhämta information i avgränsade frågor. I SSM:s Technical note-serie rapporteras resultaten från dessa konsultuppdrag.

Projektets syfte

Syftet med detta granskningsuppdrag är att studera om de landskapsmodeller som SKB använder är lämpliga och tillräckliga för sitt ändamål, speciellt i jämförelse med de referensbiosfärsmodeller som rekommenderas av BIOMASS (IAEA, 2003). Särskilt ska det dataunderlag som SKB använder analyseras för att undersöka om det är lämpligt och tillräckligt för sitt ändamål.

Författarnas sammanfattning

Som en del av SSM:s inledande granskning av SKB:s säkerhetsanalys SR-Site, av det föreslagna slutförvaret för använt kärnbränsle i Forsmark, fick Quintessa uppdraget att undersöka om de landskapsmodeller och data som används av SKB är lämpliga och tillräckliga. Resultatet av Quintessas granskning sammanfattas i denna technical note.

I biosfärsdelen av SR-Site gör SKB uppskattningar av radiologisk risk utifrån antaganden som är "så realistiska som möjligt". Detta tillvägagångssätt bygger på ett omfattande och detaljerat program för att karaktärisera den ytnära miljön i Forsmark och en rekonstruktion av utvecklingen av landskapet sedan den senaste inlandsisens reträtt för ca 10 000 år sedan. Detaljeringsgraden i rekonstruktionen och i de analyser den bygger på, samt kvaliteten på det vetenskapliga arbetet, är imponerande. En konsekvens av en metod med ett så starkt fokus på detaljer är dock att den kan hindra identifiering och motivering av de antaganden som oundvikligen måste göras vid projektioner av landskapets utveckling över långa tidsperioder.

Trots den höga kvaliteten på SKB:s program för datainsamling uppstår därför frågor om i vilken grad realism måste blandas med pragmatism för att kunna uppskatta effekten av ett eventuellt framtida utsläpp av radionuklider från förvaret genom geosfären och in till biosfären. Det är inte uppenbart att SKB tillräckligt omfattande har undersökt hur känsliga modellresultat är för viktiga antaganden inbyggda i modelleringen, detta oavsett om det gäller själva systemet eller den bärande idé om hur radionuklidtransport representeras. Till viss del kan den konservativa användningen av LDF (Landscape Dose Conversion Factor) inom säkerhetsanalysen i stort, (särskilt genom användningen av högsta beräknade LDF värde över tid och över alla biosfärsobjekt) anses som tillräckligt för att kompensera sådana osäkerheter, men SKB har inte visat detta.

Grunddragen i SKB:s metod för säkerhetsanalys är konsistenta med internationella råd om biosfärsmodellering i säkerhetsanalyser, inklusive de råd som utvecklades som ett resultat av IAEA:s koordinerade forskningsprogram

BIOMASS. Men SKB har infört modelleringsteknik inom Landskapsmodellen och i underliggande modelleringsverktyg (t.ex. behandlingen av radionuklidintag genom användning av näringskedjor) som är innovativ och ovanlig i biosfärsmodellering i säkerhetsanalyser över lång tid. Det är viktigt att förstå den potentiella betydelsen av SKB:s konceptuella utveckling inom biosfärsmodellering och hur den förhåller sig till andra mer traditionella modelleringsmetoder. Liksom för säkerhetsanalysen i sin helhet är det nödvändigt att överväga inbyggda antaganden i modelleringsmetoden och om resultaten av beräkningar kan vara känsliga för en realistisk grad av variation och osäkerhet. Det övergripande syftet bör vara att ge en robust men ändå rimlig uppskattning av om ett eventuellt framtida utsläpp kan vara acceptabelt.

Granskningen har identifierat ett antal frågor som berör metod och modellstruktur och som ytterligare behöver övervägas som en del av en bredare granskning av biosfärsmodellernas robusthet i säkerhetsanalysen. Dessa innefattar:

- Processen för ”terrestrialisation” av tidigare sjöar och våtmarker som en följd av landhöjningen är ett centralt inslag i SKB:s biosfärsmodellering. Det verkar troligt att föroreningsnivåerna i den miljö som så småningom utnyttjas som jordbruksmark i denna modell är känsliga för antaganden om netto graden av landhöjningen under den period då ett utsläpp till biosfären sker. Dock, tycks detta grundläggande antagande inbyggt i modellen inte ha undersökts.
- Antaganden om det lokala samhällets exploatering av naturresurser i närheten av ett utsläpp till ytmiljön verkar inte alltid vara konservativa.
- Eventuella konsekvenser av osäkerheter i den konceptuella representationen av transport av radionuklider under ett biosfärsobjekts evolution från sjö, via våtmark, till landmiljö verkar inte ha undersökts ur ett helhetsperspektiv.

Denna technical note innehåller bilagor med specifika frågor och kommentarer presenterade som förslag till begäran om förtydliganden från SKB samt en lista över frågeställningar som skulle kunna undersökas mer i detalj av SSM och dess externa experter under nästa fas av granskningen.

Projektinformation

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SSM perspective

Background

The Swedish Radiation Safety Authority (SSM) reviews the Swedish Nuclear Fuel Company's (SKB) applications under the Act on Nuclear Activities (SFS 1984:3) for the construction and operation of a repository for spent nuclear fuel and for an encapsulation facility. As part of the review, SSM commissions consultants to carry out work in order to obtain information on specific issues. The results from the consultants' tasks are reported in SSM's Technical Note series.

Objectives of the project

The objective of this review task is to consider whether the landscape models utilized by SKB are appropriate and sufficient for its purpose especially if compared with the Reference Biosphere Models recommended by BIOMASS (IAEA, 2003). In particular, it shall be analysed if SKB's data collection is appropriate and sufficient for its purpose.

Summary by the authors

As part of SSM's Initial Review phase of SKB's SR-Site safety assessment for the proposed final disposal of spent nuclear fuel at the Forsmark site, Quintessa was given the assignment to consider whether the landscape models and supporting data utilised by SKB are appropriate and fit for purpose. This Technical Note summarises the findings of Quintessa's review.

SKB's approach to the biosphere assessment for SR-Site seeks to undertake estimations of radiological risk in a manner that is 'as realistic as possible'. This has built on a substantial, detailed programme to characterise the near-surface environment at Forsmark and a reconstruction of the development of the landscape since the most recent ice sheet retreat, some 10,000 years ago. The level of detail in reconstruction and supporting analyses, as well as the quality of the scientific work, is impressive. However, one consequence of such a strong attention to detail is that it has the potential to obscure the identification and justification of necessary assumptions that are inevitably associated with extending landscape evolution projections over long timescales.

Despite the quality of SKB's data collection programme, therefore, questions arise regarding the extent to which realism needs to be mixed with pragmatism in establishing measures of impact from the possible future release of radionuclides from the repository, through the geosphere and into the biosphere. It is not evident that SKB has comprehensively investigated the potential sensitivity of model outcomes to key assumptions embedded in the modelling approach, whether in terms of the system itself or the way it has been conceptualised to represent radionuclide transport. To some extent, the overall cautious approach taken to the use of LDFs within the wider assessment (in particular, through use of the maximum calculated LDF value over time across all biosphere objects) might be considered sufficient to outweigh such uncertainties, but this has not been demonstrated.

The basic elements of SKB's approach to assessment are consistent with international guidance on biosphere assessment modelling, including that developed through the IAEA's BIOMASS co-ordinated research programme. However, SKB has adopted modelling techniques within the Landscape Model and some of the supporting tools (e.g. the treatment of radionuclide intake via foodchains) that are innovative and unusual in the context of long-term biosphere assessment. It is important to understand the potential significance of these conceptual developments and how they relate to other, more traditional, modelling approaches. As with the assessment as a whole, it is necessary to consider embedded assumptions in the modelling approach and whether the results of calculations might be sensitive to a realistic degree of variation and uncertainty. The overall aim should be to provide a robust yet reasonable level of assurance regarding the acceptability of possible future releases.

The review has identified a number of methodological and model structuring issues that merit further consideration as part of a wider review of robustness in biosphere assessment modelling. These include:

- The process of 'terrestrialisation' of former lakes and wetland areas as a result of land rise is a central feature of SKB's biosphere modelling approach. It would seem likely that the levels of contamination in environmental media that eventually become exploited as agricultural land in this model will be sensitive to assumptions regarding the net rate of land rise during the period when a release to the biosphere takes place. However, this fundamental assumption embedded in the model appears not to have been examined.
- Assumptions regarding the exploitation of natural resources by the local community in the vicinity of a discharge to the surface environment appear not always to be cautious.
- The possible implications of uncertainties in the conceptual representation of radionuclide transport during the evolution of a biosphere object from a lake, through a wetland, to a terrestrial environment appear not to have been comprehensively investigated.

Appendices are provided in this Technical Note covering specific questions and comments submitted as requests for clarification from SKB as well as a list of topics that could be investigated in more detail by SSM and its external experts during the next phase of the Review.

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Content

1. Introduction

As part of SSM's Initial Review phase of SKB's SR-Site safety assessment for the proposed final disposal of spent nuclear fuel at the Forsmark site, Quintessa was given an assignment to consider whether the landscape models utilised by SKB are appropriate and fit for purpose. Specifically, the review scope requires a comparison to be made with the Reference Biosphere Models recommended by BIOMASS (IAEA, 2003) and consideration to be given to whether SKB's data collection is appropriate and sufficient. This Technical Note summarises the findings of Quintessa's review.

The primary reviewed documents, where SKB's approach to landscape modelling is described, are TR-11-01 (the main report) and TR-10-09 (the biosphere analysis synthesis and summary report). Other supporting documents have also been reviewed as indicated in Appendix 1.

No independent calculations have been undertaken as part of this preliminary review to test claims made by SKB in the reviewed reports. However, a simple comparison has been made with other recently-documented biosphere assessment calculations, to provide a preliminary basis for considering the validity of the Landscape Dose Factors (LDFs) used by SKB in their analyses. This comparison and its implications are incorporated as part of the overall review.

A brief discussion of the role of landscape models in undertaking safety analyses for the geological disposal of nuclear waste is presented in Section 2. This is intended to establish a context for the review that has been undertaken, and the comparison that has been made between SKB's approach and that developed in BIOMASS. The main review findings are then presented in Section 3, with specific questions/ comments relating to aspects of the reviewed reports that require clarification from SKB being provided in Appendix 2.

Key recommendations to SSM for further work are summarised in Section 4, with a list of specific issues identified as requiring additional work by SSM and its external experts during the Main Review phase being provided in Appendix 3.

2. Role of Landscape Models

2.1. Biosphere Assessment in Context

The biosphere is an integral part of the overall disposal system, even though it performs no 'barrier' function in relation to providing assurance of long-term isolation of the disposed wastes and containment of the hazard they present. Quantitative assessment of contaminant behaviour in the biosphere and associated exposure pathways is essential to enable estimates to be made of the radiological consequences of possible releases from a disposal facility, and thereby to provide health-related indicators of overall environmental safety performance.

Section 5 of the Swedish Radiation Safety Authority's regulations (SSM, 2008) concerning the protection of human health and the environment in relation to the final management of spent nuclear fuel and nuclear waste sets a limit to the annual risk of harmful effects as a result of incurring a radiation dose after closure of a disposal facility. The limit is stated as applying to a '*representative individual in the group exposed to the greatest risk*' from potential future releases. In addition, the regulations also require (Section 7) that biological effects of ionising radiation in the habitats and ecosystems shall be described.

Guidance accompanying the regulations covers the implications of adopting a quantitative limit on risk in relation to specific events, lifetime averaging and the potential size of the most exposed group. It also addresses the question of climate evolution and other associated changes (e.g. land uplift and/or subsidence) that may influence biosphere conditions relevant to assessing the consequences of a future release. It is expected that the overall assessment will take into account '*today's biosphere conditions*' at the repository and in the surrounding area, as well as reasonably predictable changes that are in agreement with the assumed pattern (or alternative possible patterns) of climate evolution.

Consideration therefore needs to be given to the biosphere systems into which future releases might occur, as well as the behaviour of people in relation to such environments. The regulatory guidance is not prescriptive in this respect, but anticipates that the types of ecosystem currently present will form the basis of the analysis and that the selection of exposure pathways (and potential combinations of exposure pathways) '*should be based on an analysis of the diversity of human use of environmental and natural resources… in Sweden today*'. The review presented in this technical note recognises the overall framing provided to SKB's analysis by this guidance.

2.2. Reference Biospheres and Landscape Models

The concept of a 'reference biosphere' pre-dates the IAEA's BIOMASS programme, but it was that co-ordinated project which firmly established and described a number of key principles for addressing the challenges inherent in biosphere assessment modelling in the context of solid radioactive waste disposal. The requirements were summarised (IAEA, 2003) as:

(a) the need to develop a consistent and justifiable set of assumptions and hypotheses regarding the definition of future biosphere systems and potential exposure groups; and
(b) the need to put in place a logical and comprehensive framework that combines such assumptions and hypotheses with relevant scientific understanding in order to enable calculations of radiological impact.

The work of BIOMASS was based on recognition that biosphere system(s) assumed in safety assessment cannot be regarded as predictions of the actual biosphere into which a future release to the biosphere may occur. In this respect, it was acknowledged that any description of the biosphere used in long-term safety assessment would necessarily invoke assumptions and simplifications, reflecting the inherent unpredictability of the near-surface environment (e.g. in relation to natural evolution of the environment as well as potential future human development) in the very long-term. The aim is therefore to ensure that choices made in undertaking the consequence analysis provide a '*robust yet reasonable level of assurance*' (IAEA, 2003) regarding the acceptability of possible future releases from a repository, through the geosphere and into the biosphere. In comparing SKB's approach with that established by BIOMASS, the review presented in this technical note is therefore guided by the broad overall objective of ensuring that key assumptions and sensitivities relating to the derivation of LDFs used by SKB have been robustly examined.

BIOMASS explored the systematic development and justification of a small set of simplified 'generic' example reference biospheres, demonstrating implementation of the underlying methodology (i.e. justification of assumptions regarding the biosphere systems and the way they are modelled) with the intention that the examples themselves would be relevant to a wide range of contexts. It was also considered that these example reference biospheres (assuming constant biosphere system properties and characteristics) could provide appropriate benchmarks against which other assessment biosphere calculations might be compared.

At the same time, it was recognised that, when assessments are being undertaken for a specific site, there is a need to ensure that knowledge of the local environmental context is suitably reflected in the assumptions that are made. In particular, the site context introduces the possibility of reflecting relevant features of a region, its climate and landscape – and their evolution – in biosphere assessment models. One important consequence of considering an evolving landscape (rather than a time-invariant system) is the potential for contamination to accumulate over time within environmental media that may be isolated at first but then become accessible as a result of changes in landform, potentially giving rise to enhanced levels of radiological exposure (e.g. agricultural use of former bed sediments).

Swedish regulatory guidance (SSM, 2008) makes no specific reference to 'Reference Biospheres', although it does highlight the importance of defining conditions for consequence assessment calculations that illustrate the most important and reasonably foreseeable factors influencing the potential outcomes. It also points out that the conditions assumed should be realistically consistent with assumptions about climate change and landform evolution. Furthermore, it is implied that '*today's biosphere conditions at the repository and its surroundings*', along with consideration of predictable changes, should be reflected in the analysis unless they are clearly incompatible with anticipated conditions at the time a release might occur. This is again coherent with the overall principles of the BIOMASS approach.

Taken alongside the underlying principles established in the work of BIOMASS, the implication is that a 'reasonable' approach to biosphere assessment requires both a firm foundation in site understanding and a demonstration of robustness to a realistic degree of uncertainty in relation to future evolution. The challenge is to ensure that the stylised assessment models used to generate LDFs are justified as being adequately representative of possible outcomes, such that they provide meaningful indicators of the radiological significance of contaminant releases.

2.3. Key Considerations

SSM's regulatory guidance (SSM, 2008) clearly stresses the importance of developing a good understanding of present-day biosphere conditions as well as the features, events and processes that are relevant to defining '*predictable changes*' in future. There is also a specific emphasis in reporting an assessment of disposal system performance (Section 11 of the regulations) on quantitative analyses of the impact on human health and the environment during the first thousand years after closure, where it is expected that biosphere conditions and known trends should be described in detail. The reasons given for this are two-fold. On the one hand it is so that '*today's biosphere*' is sufficiently well characterised to be able to serve as a key reference point for the quantitative assessment. In addition, it is expected that reporting should fully characterise the conditions that would be applicable to a conceivable early release from the repository.

Hence is it perhaps not surprising that a recurring theme in SKB's reporting of the biosphere assessment for SR-Site is one of undertaking estimations of radiological risk in a manner that is '*as realistic as possible*'. SKB indeed makes the claim (Section 3.6 of TR-10-09) that '*... it is possible to make a scientifically underpinned and realistic assessment*' based on substantial knowledge of present-day conditions at Forsmark and its past Holocene history.

Nevertheless, it is evident from the regulatory guidance that quantitative assessments covering long time periods into the future (i.e. beyond 1000 years) are expected not only to represent today's conditions (and related predictable changes) but also to provide suitably robust indicators of radiological consequence relating to long-term environmental change. It is here that the claim to be realistic becomes subject to a broader test of fitness for purpose than simply whether or not the model provides a good representation of the present day and current trends (e.g. associated with current rates of land rise). Whilst the 'snapshot' provided by a thorough characterisation of present-day conditions and interpretation of past changes through the Holocene offers a valid and important reference point, there is a wider question to be addressed regarding the extent to which that specific pattern of landscape evolution is sufficient to characterise a reasonable range of possible future outcomes, particularly over the long term. Put more simply, is the landscape evolution model used in SKB's assessments fit for purpose to serve as the basis for assessing the radiological consequences of possible future releases?

Such a question of fitness for purpose lies outside customary understanding of the meaning of model validation. For example, it raises the question of what constitutes a reasonable level of assurance when set against the inherent unpredictability of the near-surface environment. Nevertheless, there are a number of approaches to address the overall challenge of assessing and demonstrating suitability, including:

(a) Comparing the outcomes of site-specific assessments with the results of more generic 'reference biosphere' assessment models. It is relevant to ask whether the differences can be explained and understood, either in terms of the conceptual and structural representation of the biosphere system or the choice of parameters of the contaminant transport and exposure pathway models. Moreover, in cases where reference biosphere models deliver higher 'dose conversion factors' (i.e. estimated annual dose to a member of the most exposed group per unit activity release of a specific radionuclide), it is appropriate to ask whether the conditions in which such impacts are calculated to arise are unrealistic as far as potential reasonable future conditions at this particular site are concerned. It is noted that SKB's analysis (Section 5.5 of TR-10-06) compares LDFs against results of earlier (SR-97 and SR-Can) biosphere assessment studies, but no wider analysis appears to have been undertaken against generic 'reference biospheres'.

(b) Undertaking sensitivity analyses of landscape model outcomes with a particular emphasis on those parameters that describe the system itself (and its evolution) rather those involved in modelling the behaviour of radionuclides or assumed exposure pathways. In this context it is important to recognise that certain features of the dynamic landscape and its relationship to the geosphere-biosphere interface may be reasonably well characterised at the present day, but could be significantly more uncertain in future. Such a sensitivity analysis is particularly relevant in the context of an evolving landscape because it helps to establish which assumptions (based on present-day observations) regarding properties of the system and about the nature of contaminant releases into the system may be particularly significant from the perspective of determining the potential dilution and accumulation of contaminants in future. The system uncertainties considered by SKB are described in Section 5.1 of TR-10-06.

(c) Examining the potential implications of modelling uncertainties, including the way in which features, events and processes are mathematically represented, as well as uncertainties relating to the behaviour of radionuclides in environmental media. Whilst this encompasses 'standard' approaches to parametric sensitivity analysis, it also requires consideration of how the biosphere system and its assumed evolution are interpreted within the underlying mathematical model structure (e.g. compartment sizes, turnover rates and connections). SKB's examination of model uncertainties is described in Section 5.2 of TR-10-06.

(d) Determining which potential exposure pathways are dominant in the overall derivation of dose conversion factors and considering whether alternative 'reasonable' combinations of pathways might be consistent with the expectation that the selection of pathways in the model '*should be based on an analysis of the diversity of human use of environmental and natural resources… in Sweden today*' (SSM, 2008). SKB's analysis of the significance of assumptions relating to utilisation of natural resources is addressed as part of the treatment of system uncertainty and presented in Section 5.1.2 of TR-10-06.

It is appropriate to acknowledge that a number of recognised pessimistic simplifying assumptions have been built into the landscape and dose assessment models used by SKB. These include, for example, the extent to which locally-derived resources are assumed to support the population associated with a given biosphere object and the use of the maximum calculated LDF value over time across all biosphere objects as the sole basis for estimated the radiological impacts of a release. Such a cautious approach is common to most long-term biosphere assessments and, as a general rule, is undertaken because it simplifies considerably the complexity of the models and interpretation of outcomes. Typically, such conservatisms will be retained so long as the overall outcomes of the consequence assessment do not significantly challenge regulatory limits. Hence, there may be well be scope for reducing the degree of pessimism built into the Landscape Models were it to be determined that changes to the models were merited in the light of other, currently unrecognised, uncertainties.

Nevertheless, from the perspective of considering the overall fitness-for-purpose of the assessment biosphere models used by SKB, it remains important to examine whether current assumptions embedded in the models are sufficiently robust to underpin overall confidence in estimates of the consequences of possible releases to the biosphere in the long term. The challenge is to show that a representation based on '*today's biosphere conditions at the repository and its surroundings*' (including understanding of development over the Holocene) provides a sufficient level of assurance regarding the acceptability of possible future releases.

3. Main Review Findings

3.1. Site Characterisation and Interpretation

SKB has undertaken and extensive and detailed site characterisation programme at Forsmark, which has enabled an integrated description to be assembled of the present day landscape as well as known factors affecting its development. The primary point of reference describing how the site characterisation work has been interpreted in the description of the biosphere system and its evolution is TR-10-05.

A fundamental component of the interpretation is a reconstruction of the development of the landscape since the retreat of the Weichselian ice sheet (approximately 8800 BC) and its implications for landform and ecosystem development. This reconstruction, coupled with alternative sets of assumptions regarding future climate change, then forms the basis for long-term projections of future landscape change over a period of approximately 120,000 years (roughly the length of the last glacial cycle).

The detail in the reconstruction and the supporting site investigations is substantial and impressive. Whilst it has not been possible to examine the underlying data reports from site investigations within the scope of the review described here, there is clear evidence in the principal documentation that SKB has examined and sought to characterise a wide range of landscape features, both in terms of abiotic elements and ecosystems, as well as land use. The presentation of system characterisation understandably does not mechanically follow the framework set out in BIOMASS documentation for system identification and justification, but all the relevant elements are present.

One question that might be raised regarding the approach taken is that the emphasis on such a thorough 'bottom up' characterisation of the present day and reconstruction of its development (i.e. seeking to be '*as realistic as possible*') could work against the ultimate objective of ensuring that the assessment biosphere model is sufficiently robust to reasonable variations in future conditions. The strong attention to detail (underpinned by thorough scientific investigation and analysis) thus has the potential to obscure the identification and justification of necessary assumptions that are inevitably associated with extending landscape evolution projections over long timescales.

The landscape evolution projections are intended to be consistent with the 'climate cases' and representative climate domains that have been adopted as part of the wider safety analysis. However, whilst the potential development of, and variation in, ice sheet cover over the site is of central interest to performance of the engineered barrier system, it is of less direct relevance to representation of surface systems into which radionuclides might emerge. The focus in landscape modelling is therefore on those cycles that emphasise the potential for release to terrestrial or coastal environments and within which the likelihood of resource exploitation by human communities is highest. This would seem to be an appropriate focus for the development of biosphere assessment models, although it could perhaps be argued that a stronger case for ignoring alternative climate evolution cases is merited in relation to the examination of impacts on non-human biota.

For the purposes of this particular preliminary review, we have not reviewed in detail the arguments used by SKB to justify the identification and selection of climate cases. Nevertheless, we note that the reference glacial cycle used by SKB, whilst an obvious initial choice for analysis that has evident continuity with reconstructions of landscape development over the Holocene, can hardly be considered a probable scenario in terms of projections of future climate conditions and overall landscape change. Rather, on the basis of current scientific understanding that underpins the work of the Intergovernmental Panel on Climate Change, the global warming and even the extended global warming cases must be considered much more likely.

From the perspective of the overall safety analysis, and consistent with regulatory guidance (SSM, 2008), SKB recognises that alternative climate evolutions should – at least in the first instance – be considered equally likely for the purposes of evaluating calculated risks and comparing results with the regulatory criteria. However, it could be argued that, by choosing to identify one case as the 'reference' or base-case scenario, there is an inevitable focus in the characterisation of landscape evolution on the characterisation of that case, with other alternatives potentially being treated less thoroughly as 'variants'. Anchoring the model in this reference case is perhaps consistent with the stated aim of using present-day understanding to make the analysis '*as realistic as possible*'. However, there is a risk that some aspects of the global warming cases, in particular, which could have significance from the perspective of confidence in biosphere assessment modelling assumptions, may not have been as thoroughly examined as would otherwise have been the case had they been identified with the 'reference' scenario. Examples of potentially sensitive biosphere system assumptions related to global warming cases, referred to later in this review, include global sea-level and its implications for the assumed rate of shoreline displacement, as well as the potential requirements for irrigation under warmer, drier local climate conditions.

It is notable that the focus in developing descriptions of the natural evolution of the site is exclusively on global/local climate change, including its implications for ice cover (and hence isotatic loading/rebound). The BIOMASS report (IAEA, 2003) sets out a systematic basis for examining features, events and processes relating to the changes in the system environment and its response, with the intention that this could be used to develop an audit trail for decisions relating to the representation of biosphere system evolution. Whilst it is not necessarily expected that SKB would mechanically have followed the BIOMASS procedure, it would be helpful if a more explicit analysis had been presented in the landscape report (TR-10-05) of the choices and decisions made in relation to what were deemed appropriate and/or ‘predictable’ contributions to landscape change. This, in turn, would have provided confidence that systematic consideration had been given to the identification key processes relevant to landscape change, their representation and parameterisation.

3.2. Embedded Model Assumptions

Any model of the evolution of landscape and its implications for the consequences of potential future releases to the surface environment will necessarily be founded on assumptions relating to both the system itself and the way it is represented. It is the task of the assessment modeller, and the sensitivity and uncertainty analysis that they undertake, to identify those assumptions that have the most significant potential to affect the outcomes of the model calculations. In some cases, it is indeed appropriate to use the desire for ‘realism’ as justification for assumptions that are made; in others, the task of showing that the approach is appropriate may be simplified by demonstrating that a particular assumption or approach will be conservative in so far as the outcomes will, if anything, tend to be overestimated. Sometimes the assessment results may be particularly sensitive to those assumptions, in other cases they are not.

The SKB summary report on the determination of LDFs (TR-10-06) incorporates a specific section devoted to the exploration of uncertainties and their effect on the assessment model outcomes. It is not within the scope of this particular review to consider all aspects of this analysis and, in particular, the treatment of uncertainties in radionuclide-specific parameters, or particular aspects of process conceptualisation. However, attention has been given here to the identification of certain key parameters relating to the description of the landscape and its evolution. In addition, consideration has been given (Section 3.3) to some potentially relevant aspects of model conceptualisation that appear not to have been comprehensively justified or explored as potentially significant sources of uncertainty. In both cases, the review has considered the basis for biosphere analysis described in the supporting reports (particularly TR-10-09) and the extent to which this is reflected in the quantitative examination of uncertainties and sensitivities.

In examining the potential for unrecognised key assumptions to be embedded in SKB’s analysis, the primary focus has been on the potential for associated processes to give rise to higher rates of accumulation of contamination in abiotic media than might otherwise be the case. From a system evolution perspective, the uncertainty analysis undertaken by SKB (Section 5.1.1 of TR-10-06) suggests that most important recognised uncertainties relate to assumptions regarding the timing and location of future releases to the biosphere, as well as the selection of a single 'representative' (maximum) dose conversion factor for each radionuclide, regardless of when that release occurs. In each case, SKB claim that the treatment in their baseline analysis is cautious, and the sensitivity analyses are therefore effectively geared towards understanding just how conservative those assumptions might be.

The reasons for why these, and no other, aspects of biosphere evolution have been considered are not evident from the reporting in TR-10-06. It is noted that the analysis is intentionally focused on the effects of uncertainties on dose conversion factors for long-term releases during an interglacial period, when it is generally expected that potential impacts of radionuclide release (on local human populations) will be greatest. It is also focused on those radionuclides that are found to make the highest contribution to overall calculated doses.

The analysis therefore appears to be missing a more extensive and systematic examination of the modelling elements and underlying assumptions relating to characterisation of the biosphere system and its evolution that are potentially most relevant to determination of calculated doses. It would not be appropriate develop an in-depth shadow analysis of potentially significant assumptions of as part of the present preliminary review; however, two issues are highlighted here that merit further investigation as part of the overall examination of robustness in the SKB's assessment modelling assumptions. As noted in Section 3.1, both issues are related (at least in part) to system assumptions associated with global warming climate case.

3.2.1. Combined effects of land and sea level rise

The assumed net rate of land rise (associated with post-glacial isotatic rebound) is effectively an embedded characteristic of SKB's landscape model. It is recognised (e.g. Section 10.3.3 of TR-11-01) as a key 'process of importance' for long-term biosphere development and, hence, estimated radiological impacts. The evidence that underpins the assumed rate of change in relative sea level of 6 mm per year over the next 1000 years is summarised in Section 4.1.3 of TR-10-05. It is noted in SKB's documentation that this figure is based on the assumption of a constant absolute sea level. A lower figure is assumed for the following time period (from 1000 years after closure to the end of the Temperate climate domain in the reference climate case), eventually becoming insignificant after some 30,000 years, but this is not significant from the perspective of the landscape model because the changes of greatest significance (e.g. gradual evolution from marine, though lacustrine to terrestrial ecosystems) at locations where releases are most likely to occur will have taken place over a period of less than 1000 years.

The analysis of glacial isostatic adjustment also recognises that initial rebound in the period after deglaciation was somewhat higher than the reference rate, at approximately 35 mm per year. However, based on the assumption that the future evolution of landscape will reflect that which has taken place during the current interglacial, the effective rate of land rise used in the assessment model (to reflect that relevant to discharges in the vicinity of the repository) is taken to be the same as that occurring at present. This is described by SKB as providing a predictable succession of major ecosystem types in relation to shoreline displacement.

It is recognised as a pessimistic assumption in the overall safety analysis that the LDFs selected for assessing impacts of release are those that yield the highest annual dose per unit release. What is not evident from SKB's analysis, however, is the significance of assuming that, whenever a release to the biosphere takes place, the effective rate of land rise is fixed at 6 mm per year. The potential importance of this assumption is evident from the overall results presented in, for example, Figure 10-3 of TR-10-09. The 'transitional stage' between a marine and terrestrial receptor is associated with a marked increase (by several orders of magnitude for some radionuclides) in the calculated LDF, first as the land starts to emerge from the sea, and subsequently as a result of the accumulation of radionuclides in peat, until at a defined point (when the land is 2m above sea level) the natural wetland is transformed into agricultural land.

No evidence was found in the reviewed documents of a systematic examination of the potential range of variation in vertical displacement rate or its implications for the determination of LDFs. There are at least two potential sources of uncertainty in the rate that might apply at the time any release occurred. First, it is not inconceivable that the depression caused by ice sheet cover during the next glacial cycle could be significant different from that which occurred during the Weichselian. Consequently, the rate of rebound might also be rather different from that which has taken place during the Holocene. Second, even over the next 1000 years, it is conceivable that the net rate of land rise might be somewhat lower than that currently taking place, because of the effects of global sea level change.

The latter point is acknowledged in the synthesis report (Section 10.6 of TR-11-01) and in the SR-Site climate report (TR-10-49), where it is examined as a component of the global warming climate variant. In particular, the following points are made:

> '*Due to the near-coastal location of Forsmark, the surface conditions at the site are sensitive to changes in sea level and shore line position. Such changes could be caused by effects of future global warming climates on the present glaciers and ice sheets. At present, there are major uncertainties in the estimates of future sea-level rise due to global warming. A major part of this uncertainty relates to the response of the cryosphere to increased temperatures.*'

It is nevertheless acknowledged that current projections of global sea level change as a result of glacier and ice sheet melting in a warmer world encompass the possibility of an overall rise at the coastline of Fennoscandia during the next 1000 years that is broadly comparable with the projected isostatic land rise at Forsmark. Some possible implications of this are explored in the discussion of the greenhouse climate variant, but the analysis appears to be limited to an examination of the potential for a marine transgression to take place (compared with the baseline assumption for this variant that land surface at the site remains above sea level throughout the next 120,000 years). There is no evident analysis of the potential for sea level rise to affect the net rate of land rise, which could conceivably still be positive but significantly slower than the assumption in the landscape model of 6mm per year.

In the absence of a mathematical implementation of the landscape model, it is not possible for the reviewers to say whether changes in the assumed rate of land rise would have a significant impact on calculated doses at the time the natural wetland is transformed to agricultural land. However, qualitative reasoning suggests that a slower rate of net land rise could conceivably result in a substantially longer period during which radionuclides might accumulate in a peat/wetland environment, prior to being drained and exploited as agricultural soils (i.e. once the land is 2m above sea level).

Given that future land rise following a future glaciation might also be different from that occurring at the present day, it would therefore be interesting to explore whether a reasonable variation in the rate of land rise would have a significant impact on the calculated LDF for key radionuclides.

3.2.2. Exploitation of natural resources by the local community

A further embedded component of the landscape model relates to fixed assumptions regarding how the local community makes use of natural resources. As a general rule, SKB has recognised that these assumptions are necessarily arbitrary (it is not possible to predict how future generations will exploit the environment), and the decision has therefore been made to adopt reasonably cautious assumptions that will tend to maximise potential exposures from radionuclides present in environmental media, while being consistent with '*the diversity of human use of environmental and natural resources… in Sweden today*' (SSM, 2008).

Leaving aside assumptions relating to the definition and evaluation of exposure pathways in their own right, there are a number of aspects of human behaviour (and use of local environmental resources) that do not necessarily fall into the category of cautious assumptions. Examples that have been identified as part of the current review are summarised below.

- A key embedded assumption regarding human behaviour is that contaminated wetland will be drained and exploited for agricultural use as soon as practicably possible (i.e. once the land is 2m above sea level and salt water intrusion is no longer likely). Supporting studies refer the possibility of wetland being converted to agricultural land '*at any time*' after this point (Section 8.2.2 of TR-10-05); however, once the wetland has been drained to enable agriculture to take place, the potential for further contamination through contaminated groundwater discharge becomes much weaker (and is, indeed, ignored in the assessment model). It is stated elsewhere (Section 8.4.3 of TR-10-09) that, for the purposes of calculating doses, radionuclides are assumed to accumulate continuously in wetland during the simulation period, and that conversion to agricultural soil takes place '*at the point in time that results in maximum doses*'.

  The time at which agriculture is assumed to be started during the evolution of the terrestrial environment as a result of land rise is potentially a key sensitive parameter in the assessment calculations. It would be helpful if SKB could provide more detail on the nature of the calculations undertaken, for example in terms of projections of the continued accumulation of different radionuclides in wetland over time.

- It is assumed that livestock rearing and fodder production takes place solely on drained wetland, once the land surface has risen to a level of 2m above sea level. However, it is certainly not inconceivable (especially in a warmer world, with less dependence on fodder production for winter feeding) that livestock would be allowed roam more extensively and therefore have access to contaminated wetland areas and natural pasture. It is not necessarily the case that allowing for such practices would lead to a significant change in the calculated overall LDF, but it would interesting to see such an assumption explored as part of the overall sensitivity analysis.

- Irrigation of agricultural land with well water is considered an unlikely practice (on the basis that surface water will be readily available '*in most biosphere objects*') and is therefore excluded from baseline calculations using the landscape model. This is clearly not a cautious assumption; nevertheless, the potential implications of short-term irrigation (over a period of c.50 years) are explored as part of the model sensitivity analysis (Section 5.1.2 of TR-10-06), suggesting that LDF values for a few radionuclides (including Ra-226) might be increased by a factor of 2 to 3. In this context, it is also worth noting that the particular landscape object that yields the highest LDF for most radionuclides (121_3) does not go through a 'lake' stage; hence the assumption that surface fresh waters will be readily available for irrigation may well be less valid.

  The value assigned to the corresponding model parameter (*vol_irrig*) is understood to be based on a characteristic value derived for typical Swedish conditions of 0.15 m^3m^{-2} per year (TR-10-01), coupled with a typical requirement of five irrigation events per year. The assumed rate of irrigation with well water used in the sensitivity analysis is not entirely clear, but the text suggests that it is assumed that '*well and surface water are equally likely to be used for irrigation*'. This presumably means that the assumed irrigation rate with well water in the sensitivity study is in fact half the total assumed irrigation requirement, which would again be a non-cautious assumption.

  Moreover, the assumed irrigation rate is understood to be based on present-day conditions in Sweden and no account has been taken of the possibility of increased demand for irrigation under future greenhouse-warmed conditions. SKB asserts (Section 12.2.2 of TR-10-09) that surface water runoff would in fact increase at the site with increased seasonal temperatures, making the use of surface waters even more likely than under present-day conditions. However, the assertion of greater surface water availability in warmer climate conditions appears to rest on a study (TR-09-04) that indicates the likelihood of a more widespread wintertime maximum related to high seasonal precipitation and lack of snow. Increased stream water flows and lake levels during the winter months are unlikely to be relevant to determining availability of irrigation waters that may be required in the summer, unless it were assumed that drainage water was stored. It is not immediately evident that collection and storage above ground would be a preferred practice compared with groundwater abstraction.

  It would therefore be instructive to examine the sensitivity of calculated LDFs to a reasonable variation in irrigation rate, especially under the assumption that such water might be drawn from underground sources.

  The possibility of long-term irrigation (whether by surface water or well water) is excluded altogether by SKB for the organic soils that would be derived from drained wetlands in the Forsmark area, on the basis that they would be productive for agriculture only during a limited time. However, sensitivity studies were undertaken under the assumption that contaminated surface waters might be used over a long time period for the irrigation of (initially uncontaminated) minerogenic soils derived from glacial and post-glacial clays in Öregrundsgrepen (Section 5.1.2 of TR-10-06). Such a process could potentially lead to a long-term gradual build-up of radionuclide concentrations in the soils; nevertheless, the derived concentrations in vegetables were substantially below those calculated for short-term use of organic soils initially contaminated by the accumulation of radionuclides in peat. It is not clear why SKB chose to exclude the possibility of long-term irrigation using more highly contaminated well water from this aspect of the sensitivity analysis.

3.3. Conceptual Models

Exploration of uncertainty associated with choices that are made in relation to conceptualisation of the biosphere system to derive mathematical models of radionuclide transfer is an essential component of the assessment. As noted previously, SKB has undertaken an examination of the potential importance of some conceptual modelling uncertainties as part of the SR-Site landscape model analysis, as described in Section 5.2 of TR-10-06.

The issues covered in the analysis include some aspects of the way in which the compartment model for biosphere assessment has been spatially discretised. In addition, an analysis has been made of the potential implications of the simplifying assumptions adopted in order to represent specific radionuclide transfer processes, with a particular focus on water mediated transport within the regolith. Specific attention is given to the treatment of advective transport at the geosphere-biosphere interface, represented by the 'lower regolith' compartment.

3.3.1. Conceptual innovations in the landscape model

Two major conceptual features of the landscape compartment model, which differentiate it in structural terms from the majority of biosphere models used in other long-term safety assessments (whether by SKB or others) are that it:

(a) has the capability to represent an interconnected network of biosphere objects, each of which is associated with the local topography of a sea or lake basin and may be associated with a groundwater discharge;

and

(b) is able to represent each object as a dynamically evolving sub-system, according the effects of shoreline displacement, sedimentation and erosion, infilling and ecosystem succession.

Given this, there is clearly an interest to understand the significance of specific conceptual modelling assumptions relating to these novel features. The potential significance of the network approach and, in particular, the possibility that a given object might receive contaminant inputs both from the geosphere and from other, ‘upstream’ objects is discussed in SKB’s report describing the derivation of LDFs (Section 5.2.1 of TR-10-06). The analysis is not fully presented in the report, but it is claimed to show that, provided the conservative assumption is made that the highest calculated LDF value over time across all biosphere objects is used as the single ‘representative’ dose conversion factor for each radionuclide, the same value will be used regardless of whether the objects are treated as a network or not. This claim cannot be tested, however, without better access to the underlying results or through independent modelling.

The other key innovation, representing the dynamic evolution of each biosphere object, does not appear to have been reviewed at all from the perspective of examining the implications of conceptual model uncertainty. For example, a fundamental consideration in the dynamic model is the representation of accumulation in specific model compartments, followed by the subsequent ‘transfer’ of their content to a different compartment as a consequence of assumed effects of land rise on drainage, sedimentation and ecosystem evolution. This feature of the model is a critical aspect of the overall landscape model, in so far as the effects of such accumulation and transfer, coupled with assumptions regarding cultivation of drained wetlands, has a major impact on the derivation of LDFs.

Specifically, the representation of terrestrial ecosystem development (the scientific underpinning for which is outlined in Section 5.1.2 of TR-10-05) incorporates a transport process between model compartments that is identified as ‘*terrestrialisation*’. This process causes radionuclides that had formerly accumulated in aquatic sediments (i.e. both the upper and mid ‘aquatic regolith’) to be transferred to ‘middle terrestrial regolith’ compartment. This is because the ‘upper terrestrial regolith’ compartment is assumed to be associated with the development of peat through sedimentation and the establishment of pioneer vegetation.

One possible reading of the model description (e.g. Section 8.4 of TR-10-09) is that an initially uncontaminated peat layer is assumed to be instantaneously established above the ‘middle terrestrial regolith’ compartment. The conceptual model then assumes that the sole route for contamination of the peat is water flux from the underlying gyttja and clay-gyttja layers, linked to the fact that wetlands tend to be associated with areas of groundwater discharge. Following drainage, agricultural soils are assumed to be developed through the mixing of organic matter with the deeper mineral (former sediment) layers.

It is understandable that the current model may invoke necessary simplifications, but it is also relevant to ask (as with other conceptual assumptions) whether these are necessarily cautious in relation to the eventual incorporation of accumulated contamination into agricultural soils. For example, given that the representation of ‘terrestrialisation’ as a compartment model transfer, as well as the process of arable land development, are such critical aspects of the model, it would be instructive to examine the sensitivity of calculated LDFs (or, more specifically, calculated concentrations in agricultural soils) to possible alternative assumptions regarding how peat becomes contaminated (e.g. by root uptake into pioneer vegetation) and the rate at which it is developed. More generally, the overall description of this fundamental element of model conceptualisation is difficult to follow in the biosphere modelling synthesis report (TR-10-09) and is not explained any more clearly in the SKB report on terrestrial ecosystems (TR-10-01). Hence the precise nature of such sensitivity analyses proposed above may be difficult to specify without further clarification of the precise ‘wiring’ of the conceptual model for radionuclide transport, in particular with respect to its representation of a dynamically evolving system.

3.3.2. Foodchain models

There are several references in the biosphere assessment documentation to the novel approach to foodchain exposure modelling that has been developed by SKB as an alternative to more traditional dietary-based food consumption models. The overall principle is that human inhabitants make maximum use of available food sources within a biosphere object, with the contribution from different food types being dictated by production capacity of those foods.

Whilst it has been possible to locate descriptions of some of the data used in (or derived from) the foodchain model (e.g. the specification of food intake in Section 6.4.2 of TR-10-07), the review undertaken in preparation of this technical note did not reveal any formal documentation of the foodchain model itself. Descriptions of the model (e.g. Section 3.2.3 of TR-10-06; Section 8.3.3 of TR-10-09) provide a glimpse of the approach, but it was not possible to trace a published description of the methodology. For example, it is unclear whether it is embedded in the PANDORA code, or whether a completely separate calculation method is used.

It will be important for SSM to understand the conceptual basis of the food pathway model and the extent to which it has been examined and challenged in terms of its potential contribution to overall uncertainty and the robustness of calculated LDF values.

3.3.3. Geosphere-biosphere interface

There is no explicit coupling between the groundwater radionuclide transport modelling and the biosphere assessment models used in SR-Site. This is neither unusual nor surprising – the challenges of establishing a fully integrated model are significant. It is therefore necessary to establish a consistent conceptual understanding of the interface between the geosphere transport and landscape models for radionuclides.

So far as the reviewers have been able to discern, however, consideration of the geosphere-biosphere interface is solely addressed within the biosphere component of the safety analysis. Near-surface hydrology is given specific attention in the underpinning landscape descriptive report (TR-10-05) and is explored further through regional flow modelling using the MIKE SHE tool (as outlined in Section 7.1 of TR-10-09). By contrast, the groundwater transport modelling (based on FARF31 and MARFA) is informed by bedrock hydrogeology modelling (using ConnectFlow) that extends to the surface, but – although ConnectFlow does calculate specific discharge points – the transport models do not seek to attribute calculated fluxes to specific potential discharge areas. Nevertheless, the outputs from ConnectFlow (at a depth of 40m below present sea level) have been used to establish initial input conditions for the MIKE SHE tool.

Because of the nature of the disposal system, the primary focus of the consequence analysis is on transport originating at a single spent fuel disposal canister. It is not possible to define, a priori, those deposition holes within the engineered system that are likely to be associated with potential releases on the timescale of the assessment so, in practice, the geosphere-biosphere interface could be any one of a number of locations in landscape, depending on where it is assumed that the original source is located. The primary function of the near-surface hydrogeological modelling using MIKE SHE is to determine where possible future discharge areas might be (and, indeed, where they are not expected to be). This, in turn, serves to guide the identification of those (present and future) lake basins within the Forsmark landscape, defined by topography, that are of significance for the biosphere assessment model.

It is noted in the biosphere synthesis report (Section 7.2.2 of TR-10-09) that the MIKE SHE and ConnectFlow particle tracking models do not necessarily agree where releases starting at the same point 40m below sea level will emerge at the surface. As a general rule, MIKE SHE discharge locations tend to be more concentrated along the shorelines (or former shorelines) of terrestrial lakes, whereas those from the ConnectFlow models tend to appear in the central parts of lakes. Nevertheless, there is evidently good agreement regarding which biosphere objects are potential receptors.

The fact that the independent MIKE SHE and ConnectFlow models are in general agreement regarding transport pathways in near-surface hydrogeological system lends some confidence to the way in which such modelling has been used to underpin the landscape model and simplify the representation of the network of relevant biosphere objects. However, it would be likely to be beneficial to the overall understanding of confidence in the landscape models if a more systematic exploration of potential uncertainties in the flow models and their implications could be incorporated as part of the wider examination of conceptual modelling. In addition, it would be valuable to consider in more detail whether the precise discharge location within a defined biosphere object is likely to have a significant influence on the subsequent transport and accumulation of radionuclides within the biosphere.

Discharges to the landscape model are conceptually represented as inputs to a single ‘lower regolith’ compartment. Assumptions relating to the vertical discretisation of this compartment are explored as part of the landscape model sensitivity analysis (Section 5.2.1 of TR-10-06). However, there is a broader question of whether it is appropriate effectively to dilute the discharge by averaging over (say) the whole sub-catchment area associated with the biosphere object, rather than considering more directly the implications of a more localised discharge (as simulated by particle tracking within the MIKE SHE models). It might be argued that potential doses to people linked to the higher concentrations associated with a smaller discharge area would necessarily be ‘diluted’ within a local community by the use of resources from non-contaminated areas associated with the same biosphere object.

It is perhaps less appropriate to assume such effective dilution in relation to the evaluation of potential exposures of non-human biota. Although considerable attention is devoted to the description of the underlying hydrogeological modelling, this conceptual issue relating to the determination of potential radiological impacts resulting from the discharges appears not to be discussed.

3.4. Exposure Pathways

SKB's uncertainty analysis relating to the derivation of LDFs includes an element that is related to potential uncertainties in the representation of exposure pathways (Section 5.1.2 of TR-10-06). In many cases, it is argued that the approach taken (e.g. in relation to assumed occupancy of potentially contaminated areas and the local derivation of foodstuffs) represents a cautious simplifying assumption.

One important aspect of the dose assessment is that the baseline calculations make no pre-defined assumptions regarding the specific dietary composition in the calculation of doses from food ingestion. Instead, it is assumed that the implicit contribution of different food types to diet is proportional to the production capacity of those food types within a biosphere object. This leads to outcomes that are not readily transparent, in so far as it is difficult to interpret the results in relation to an actual diet or to understand whether the dominant food groups contributing to dose are a reasonable reflection of what might be incurred from an actual diet. SKB's uncertainty analysis suggests that uncertainty with respect to human diet is less important than uncertainty relating to land use, primary productivity and estimated concentrations in different foodstuffs. Nevertheless, the underpinning 'primary productivity' model for estimating doses from foods remains somewhat opaque, rendering overall results difficult to interpret.

It would also be instructive if an examination could be made of more 'exotic' potential exposure pathways that are nevertheless broadly consistent with present-day or recent historical human activities. Examples potentially include the impacts (in terms of both external irradiation and inhalation exposure pathways) of cutting, storing and using peat as a fuel.

3.5. Overall Approach to Assessment

Several times in the documentation of the biosphere assessment, SKB makes the claim that the modelling approach is '*as realistic as possible*'. Indeed it is explicitly stated (Section 3.6 of TR-10-09) that this is SKB's goal.

However, as has been noted through the preceding discussion, the term 'realistic' needs to be interpreted in the context of a long-term assessment that necessarily requires wide-ranging assumptions and simplifications to be adopted. It is also appropriate to question whether SKB's approach to the treatment of biosphere uncertainty is consistent with the claimed adoption of a realistic approach.

The LDFs used in the overall assessment are specified single, deterministic values for each radionuclide. SKB has undertaken sensitivity and probabilistic uncertainty analyses using the models, with the aim of demonstrating that the LDFs assumed in the assessment are suitably cautious (i.e. at the top end of any distribution that might be produced).

On the other hand, it is not entirely evident that the overall approach to parameter selection within the models is necessarily pessimistic. Messages relating to the management of uncertainty (and dealing with necessarily assumptions and simplifications) are scattered throughout the biosphere assessment reports, suggesting that higher level documentation would benefit from better integration on this issue. In particular, it would be helpful to show how the principles adopted in developing the model parameter database (TR-10-07) reflect the overall assessment philosophy that SKB claims to have followed.

SKB argues (Section 5.3.1 of TR-10-06) that the use of probability distribution functions presents significant practical difficulties, particularly in relation to providing consistent correlations between parameter values and the potential for generating distributions of LDF values that are long-tailed and with large standard deviations. Nevertheless, a 'realistic' approach to assessment could be taken to imply that realistic parameter ranges ought to be explicitly incorporated in the baseline calculations. This does not necessarily imply that the expectation value of the resulting LDF distribution should be selected as the representative basis for assessment; rather that a realistic view of uncertainty (rather than necessarily seeking to adopt cautious parameter assumptions) should be presented as a core component of the analysis.

3.6. Comparison with Other Biosphere Models

As noted in Section 2.3, one potential contribution to confidence in the site-specific LDFs used by SKB is to compare and attempt to explain differences between the results and those obtained using more generic 'reference biosphere' assessment models.

A comparison has been made by SKB (Section 5.5 of TR-10-06) with the results of previous SR-97 and SR-Can biosphere assessment studies. Some of the differences are attributed to the use of site-specific, rather than generic assumptions regarding radionuclide parameters such as concentration ratios (for estimated uptake into foodstuffs) and partition coefficients between water and solids. Where doses are dominated by ingestion exposure pathways, LDFs estimated for SR-Site are generally higher than the dose conversion factors derived for SR-Can, whereas those that are dominated by consumption of drinking water are broadly similar.

Overall, however, the comparison with previous modelling results is somewhat superficial, including general statements, such as '*there are other differences…mainly related to improvements in the radionuclide model for the biosphere*'. Examples of such 'improvements' are identified in the report, but there is an absence of systematic discussion and explanation of differences in model outcomes for specific radionuclides (especially those found to be most significant in the overall safety analysis).

As an input to the type of comparisons that might be undertaken, the reviewers have compiled sets of dose conversion factors derived in recent generic biosphere assessment studies undertaken in the UK (Walke et al., 2011) and Switzerland (Nagra, 2010). The specific results being compared are:

- SKB: Reference climate case, long-term release during temperate conditions (Table 4-1 of TR-10-06).

- UK: Advective release to sub-soil, with irrigation using contaminated well water in Temperate, Semi-arid and Warm Humid climate conditions (Table 33 of Walke et al. (2011)).

- Switzerland: Advective release to soil ('*large area with large river*') and irrigation using well water in present-day and Warmer/Drier climate conditions (Tables A4-1and A4-2 of Nagra (2010).

Tabulated results for radionuclides found to be of key importance in SR-Site are summarised in Table 1, below. To guide a comparison, the calculated ratio of the generic dose conversion factors to the LDFs presented by SKB is shown in Table 2.

Inspection of the results suggests that there are a number of radionuclides for which the biosphere dose conversion factors (especially in the UK examples) are higher than those determined in SKB's analysis. For Ra-226, one of the most important radionuclides in the SR-Site safety assessment, the difference ranges from just over an order of magnitude under similar climate conditions, to more than 40 in the event of a warmer, drier biosphere system. It seems likely that the primary cause of the difference relates to assumptions (e.g. magnitude and duration) regarding irrigation with contaminated well water. Overall, where the results obtained using simpler generic models for temperate climate conditions are greater than the LDFs determined by SKB, the ratio is between a factor 3 and an order of magnitude.

It is not the purpose of the comparison set out in these tables to demonstrate a forensic comparison of the different models, but rather to illustrate the nature of the analysis that might be carried out. As noted earlier, the primary aim would be demonstrate the differences from simpler assessment models – and the variation between different radionuclides – can be explained and understood in terms of the specific features that are associated with the landscape models. Specifically, where any reference biosphere models were shown to deliver dose conversion factors that are higher than the LDFs obtained from the site-specific landscape model, the aim would be to explain whether or not the conditions adopted in the generic model could reasonably take place at Forsmark.

Table 1: Comparison of biosphere dose conversion factors (Sv/Bq) in recent modelling studies

Radionuclide	SR-Site	NDA RWMD			Nagra	
		Temperate	Semi-arid	Warm Humid	Reference	Warmer/ Drier
C-14	5.4 E-12	1.2 E-12	3.0 E-12	6.5 E-13	7.4 E-16	9.6 E-15
Cl-36	5.8 E-13	1.5 E-13	3.9 E-13	1.0 E-13	7.0 E-15	8.5 E-14
Ni-59	7.4 E-14	4.0 E-15	1.2 E-14	3.8 E-15	1.2 E-16	7.0 E-16
Se-79	1.2 E-09	1.6 E-12	4.1 E-12	9.5 E-13	6.6 E-14	7.6 E-13
Zr-93	2.8 E-14	3.3 E-14	1.2 E-13	4.6 E-14	7.8 E-15	2.0 E-14
Nb-94	4.0 E-12	3.5 E-12	8.7 E-12	2.2 E-12	1.6 E-13	1.2 E-12
Tc-99	9.0 E-13	2.1 E-14	7.5 E-14	2.8 E-14	5.2 E-14	8.6 E-13
I-129	6.5 E-10	3.3 E-12	1.2 E-11	4.5 E-12	2.0 E-13	1.9 E-12
Cs-135	4.0 E-14	5.8 E-13	1.5 E-12	3.6 E-13	2.8 E-14	1.2 E-13
Ra-226	3.8 E-12	5.1 E-11	1.6 E-10	5.5 E-11	2.8 E-13	1.7 E-12
Ac-227	8.0 E-12	1.2 E-11	4.6 E-11	1.8 E-11	1.0 E-15	1.7 E-15
Th-229	3.6 E-12	3.5 E-11	1.1 E-10	3.9 E-11	9.4 E-14	1.6 E-13
Th-230	1.3 E-11	9.6 E-11	2.3 E-10	4.5 E-11	3.3 E-12	2.6 E-11
Np-237	4.8 E-11	3.2 E-12	1.2 E-11	4.5 E-12	3.4 E-14	2.0 E-13
U-238	1.9 E-12	1.4 E-12	5.1 E-12	2.0 E-12	2.4 E-14	1.9 E-13
Pu-239	1.9 E-12	7.3 E-12	2.7 E-11	1.0 E-11	4.6 E-14	7.9 E-14
Pu-240	1.9 E-12	7.3 E-12	2.7 E-11	1.0 E-11	1.8 E-14	2.7 E-14
Am-241	1.5 E-12	5.8 E-12	2.2 E-11	8.4 E-12	1.0 E-15	1.3 E-15
Pu-242	1.9 E-12	7.0 E-12	2.6 E-11	9.9 E-12	8.1 E-14	1.7 E-13

Table 2: Ratio of biosphere dose conversion factors to LDFs used in SR-Site (shading highlights ratios greater than unity)

Radionuclide	SR-Site (LDF Sv/Bq)	NDA RWMD			Nagra	
		Temperate	Semi-arid	Warm Humid	Reference	Warmer/ Drier
C-14	5.4 E-12	0.22	0.56	0.12	0.00	0.00
Cl-36	5.8 E-13	0.26	0.67	0.17	0.01	0.15
Ni-59	7.4 E-14	0.05	0.16	0.05	0.00	0.01
Se-79	1.2 E-09	0.00	0.00	0.00	0.00	0.00
Zr-93	2.8 E-14	1.18	4.29	1.64	0.28	0.71
Nb-94	4.0 E-12	0.88	2.18	0.55	0.04	0.30
Tc-99	9.0 E-13	0.02	0.08	0.03	0.06	0.96
I-129	6.5 E-10	0.01	0.02	0.01	0.00	0.00
Cs-135	4.0 E-14	14.5	37.5	9.00	0.70	3.00
Ra-226	3.8 E-12	13.4	42.1	14.5	0.07	0.45
Ac-227	8.0 E-12	1.50	5.75	2.25	0.0	0.0
Th-229	3.6 E-12	9.72	30.6	10.8	0.03	0.04
Th-230	1.3 E-11	7.38	17.7	3.46	0.01	2.00
Np-237	4.8 E-11	0.07	0.25	0.09	0.00	0.00
U-238	1.9 E-12	0.74	2.68	1.05	0.01	0.10
Pu-239	1.9 E-12	3.84	14.2	5.26	0.02	0.04
Pu-240	1.9 E-12	3.84	14.2	5.26	0.01	0.01
Am-241	1.5 E-12	3.87	14.7	5.60	0.00	0.00
Pu-242	1.9 E-12	3.68	13.7	5.21	0.04	0.09

3.7. Summary of Findings

SSM has suggested that all the reviewers should consider the following issues in their review of the relevant SR-Site reports as they relate to the scope of the review:

- the completeness of the documented work;
- the scientific soundness and quality of the documented work;
- the adequacy of relevant models, data and safety functions;
- the handling of uncertainties;
- the safety significance of the work; and
- the quality in terms of transparency and traceability of information in the reports.

The findings relating to these issues for the review of SKB’s development and use of landscape models for biosphere assessment are summarised in Table 3.

Table 3: Summary Findings of the Review of SKB's Development and Use of Landscape Models for Biosphere Assessment

Issue	Finding
Completeness	**Generally good**, and especially thorough in relation to site characterisation. However, there are limitations in the extent to which certain issues of model sensitivity have been explored, which leaves open questions regarding the overall degree of robustness of the model and the Landscape Dose Factors that are generated. The primary focus of the calculations is on the reference glacial cycle, although the global warming and even the extended global warming cases must be considered more likely. A consequence of the inevitable focus on the reference case is that modelling questions that tend to arise specifically (though not exclusively) in association with the variants may not receive the same degree of attention.
Scientific soundness and quality	**Generally good**, particularly in relation to the site investigations that underpin the system description for the present day. The undertaking of independent checks of calculations is beyond the scope of the current review. It could be argued that the overall quality of the analysis is somewhat undermined by the presentation of the documentation. There is a lack of clarity, both in terms of the explanations of what has been done within the models (e.g. the treatment of ingestion pathways) and in relation to presentation and interpretation of model outcomes. There is also a substantial degree of repetition, which can make reading the reports quite challenging.
Adequacy of relevant models, data and safety functions	**Generally good**, although better information on model content and the comparison of model performance with other alternative approaches would be helpful in the supporting documentation. There are no safety functions associated with the biosphere component of the disposal system. It is important to recognise that the nature of biosphere analysis is such that it necessarily invokes a number of assumptions and simplifications that need to be identified and addressed. A very thorough analysis aimed at making the models 'as realistic as possible' runs the risk of giving much less visible recognition to the limitations inherent in using such detailed characterisation as a basis for assessment.
Handling of uncertainties	**Generally good**: however, the reasons for selection the particular sensitivity and uncertainties entering the analysis are not well set out. This review has identified a number of areas where more thorough examination of sensitivities (particularly to modelling assumptions – both in relation to system evolution and conceptual modelling) would be advantageous.
Safety significance	**Limited**: the overall safety of the repository is primarily dependent on: canister design and performance; the time of failure; the fuel dissolution rate; the advective travel time. The biosphere is part of the disposal system but is not strictly a barrier; nevertheless, biosphere dose factors need to be well justified, in order to provide a 'robust yet reasonable' assurance regarding the acceptability of potential future releases.

Issue	Finding
Quality in terms of transparency and traceability of information	**Poor**: the documentation suffers from being quite repetitive on some matters (essentially the same set of words and paragraphs appearing in several reports). This can make it difficult to follow through a particular line of argument without substantial cross referencing between reports, even when the issue at stake is being examined a relatively high level. Moreover, while some aspects of the modelling work is described in considerable detail, in other cases (e.g. in relation to a suitable high level description of the approach to foodchain exposure modelling), it is not clear whether or not relevant information is actually available.

Overall, it would seem that the regulatory expectation that a '*realistic set of biosphere conditions*' (page 5 of SSMFS 2008:37) should be adopted as a basis for dose assessments has been interpreted by SKB as a requirement for its assessment models to be very closely tied to detailed site-specific measurements. Thus, for example, the detailed site investigation programme undertaken by SKB is used to support claims that the assessment modelling is '*as realistic as possible*'.

However, it is our understanding that the intention of the regulatory guidance was simply to ensure that the *type* of ecosystem embodied in an assessment biosphere should be properly consistent with wider assumptions regarding climate and landscape evolution. It is our belief that, by focusing on providing support for claims of realism, SKB may have missed the opportunity to explore sensitivities to underlying assumptions associated with their 'realistic' approach and thereby to demonstrate more broadly the suitability of the calculated LDFs as a basis for determining the acceptability of future releases.

In this respect, we note that there is also an emphasis in the regulations on providing a detailed characterisation of '*today's biosphere*' and its anticipated evolution (based on known trends) over the next 1000 years. There are specific reasons (highlighted in the regulatory guidance) why a focus on this time period is required as part of the assessment reporting. However, whilst such a requirement points towards an analysis of the type undertaken by SKB, drawing on a detailed site characterisation programme, it is not appropriate (unless thoroughly justified) to use present-day 'realism' as the sole basis for quantitative assessments extending into the far future.

4. Recommendations to SSM

It is important not to get lost in significant technical detail when reviewing SKB's approach to biosphere assessment. The approach itself is complex, and follows a multi-layer approach involving a series of supporting models. Ultimately, however, any biosphere model used in long-term assessment – even if based on the best quality site characterisation data – cannot be expected to provide a 'realistic' analysis over a substantial timescale. Assumptions and simplifications are inevitable; it is therefore of paramount importance to understand which of these are critical to the determination of LDFs.

The main review findings have been presented in Section 3, with specific questions and comments relating to aspects of the reviewed reports that require clarification from SKB being provided in Appendix 2. The need for further review work during the Main Review Phase is, to some extent, dependent on the answers to questions raised in Appendix 2. Nevertheless, it seems appropriate that SSM will wish to set up a parallel model to enable checking calculations to be undertaken and to explore potentially interesting elements of sensitivity analysis beyond those reported in the SKB documentation.

A proposed preliminary list of specific topics relevant to SKB's landscape model , which requiring additional work by SSM and its external experts during the Main Review Phase, is provided in Appendix 3.

References

IAEA (2003). *'Reference Biospheres' for solid radioactive waste disposal*. Report of BIOMASS Theme 1 of the BIOsphere Modelling and ASSessment (BIOMASS) Co-ordinated Research Project, International Atomic Energy Agency, Vienna, July 2003.

Nagra (2010). *Beurteilung der geologischen Unterlagen für die provisorischen Sicherheitsanalysen in SGT Etappe 2. Biosphärenmodellierung: Grundlagen für die Testrechnungen*. Arbeitsbericht NAB 10-15, Nagra, Switzerland, October 2010.

SSM (2008). *Strålsäkerhetsmyndighetens föreskrifter och allmänna råd om skydd av människors hälsa och miljön vid slutligt omhändertagande av använt kärnbränsle och kärnavfall*. Swedish Radiation Safety Authority Regulatory Code SSMFS 2008:37, Stockholm, ISSN 2000-0987, January 2009.

Walke R C, Limer L and Thorne M C (2011). *NDA RWMD Biosphere Assessment Studies FY2010-2011: Biosphere Assessment Model*. Quintessa report for the Nuclear Decommissioning Authority Radioactive Waste Management Directorate, QRS-1378ZM-4, November 2011.

APPENDIX 1

Coverage of SKB reports

The SKB reports covered in this review are listed in Table A1. These include the mandatory SKB reports specified in the assignment together with a number of other reports that provide background information on detailed elements of the biosphere assessment methodology

Table A1: SKB Reports Reviewed

Reviewed report	Reviewed sections	Comments
TR-11-01 (Main report)	Sections 4.10, 10.4.2, 13.2, 13.5.7, 13.6.5, 15.6.20, 15.7.5	Other relevant sections covering climate change etc.
TR-10-09 (Biosphere analysis – synthesis and summary of results)	Whole report	
TR-10-06 (Landscape Dose Conversion Factors)	Whole report	Focus on system and conceptual modelling, rather than detailed processes for radionuclide transport and exposure
TR-10-05 (Landscape Forsmark – Data, Methodology and Results	Whole Report	Specific focus on approach to near-surface hydrogeological modelling
TR-10-01, TR-10-02, TR-10-03	Various, according to follow-up of detailed issues	Principally for background, and aspects of parameter choice
R-10-37 (Components, Processes and Interactions in the biosphere)	Overview	Supporting/background reading

Note: SSM's work specification for this review assignment also identified report TR-10-28 (Chemistry data used for estimation of CR and Kd values in SR-Site) as an example of a potentially relevant report. The report is a further example of the comprehensive nature of SKB's site-specific data gathering, but detailed review of the data themselves is beyond the scope of this methodology-focused review.

APPENDIX 2

Suggested requests for additional information from SKB

1. Several times throughout the documentation of the biosphere assessment, SKB makes the claim that the modelling approach is '*as realistic as possible*'. If this was SKB's goal (as indicated in the discussion of Assessment Philosophy in TR-10-09), how should the term 'realistic' be interpreted in the context of a long-term assessment that necessarily requires wide-ranging assumptions and simplifications to be adopted? For example, given the degree of caution that is adopted in selecting the maximum LDF value over time across all biosphere objects and other simplifying assumptions, what is SKB's view of the appropriate balance between realism and caution in the treatment of uncertainties? If the aim is to adopt a realistic approach to assessment, why has SKB not presented LDFs as uncertainty distributions, within a probabilistic framework based on realistic parameter ranges?

2. To what extent has SKB undertaken a systematic exploration of potential uncertainties associated with the application of MIKE SHE and its implications for the selection of biosphere objects within the conceptual model. Are there other methods that could be used to identify likely points of discharge? Does it matter where within a given biosphere object the release from the geosphere is assumed to take place?

3. Having developed the Landscape Model as a network of interlinked biosphere objects, it would appear that SKB has concluded that it was not actually necessary to adopt such a complex approach in deriving LDFs. What are the main reasons why this is the case for Forsmark and the SR-Site analysis, and under what circumstances does SKB imagine that the capability provided by simulation of such a network might prove to be an important aspect of biosphere assessment modelling? For example, is their conclusion dependent on assumptions about this particular network of objects, and the associated pattern of groundwater discharge (simulated with MIKE SHE), or can more general inferences be drawn? Are the calculations reported in Section 5.2.1 of TR-10-06 concerning '*Disregarding contamination from upstream biosphere objects*' reported anywhere, and can they be made available to SSM?

4. It would be helpful if SKB could provide more detail regarding the nature of the calculations undertaken in relation to agricultural use of former wetlands, for example in terms of projections of the continued accumulation of different radionuclides in wetland over time.

5. What dictated the choice of uncertainties to explore within the sensitivity analysis undertaken on the Landscape Model? How can SKB demonstrate that they have systematically covered all issues of potential relevance? For example, given the recognised significance of the process of 'terrestrialisation' of former lakes and wetland areas as a result of land rise, what steps were taken to identify uncertainties in key parameters and conceptual models relating to this process (e.g. rate of land rise)?

6. What documentation exists for the productivity-based foodchain model and its implementation for SR-Site? To what extent has the model been subject to a critical sensitivity and uncertainty analysis?

7. Given that the structure of the Landscape Model, the nature and scale of model compartments, and the treatment of the geosphere-biosphere interface have largely been framed by consideration of potential exposures to human inhabitants, how can SKB be sure that the modelling approach (e.g. in relation to temporal and spatial averaging, and the choice of representative climate futures) is also suitable for assessing potential impacts on non-human biota?

8. To what extent has SKB been able to develop a systematic understanding of why the LDFs used in SR-Site differ from those used in previous assessments (SR-Can and SR-97) or those derived in assessment undertaken by other organisations? Can clear explanations be provided of the differences for the key radionuclides in terms of the overall risk assessment, and does such an analysis add to, or take away from, confidence in the overall robustness of the assessment model?

APPENDIX 3

Suggested review topics for SSM

This appendix provides a preliminary list of topics that could be considered in further work by SSM and its external experts as part of the review of the methodology used by SKB in its biosphere assessment. The list has been sub-divided into:

- topics primarily requiring further review (and maybe some limited analysis);
- topics requiring further analysis using mathematical models; and
- topics requiring additional competence.

Topics requiring further review

1. Should more information be available from SKB regarding the composition and implementation of the foodchain model, it would be help for SSM to arrange for this to be reviewed from a methodological perspective and for consistency with the overall assessment approach.

Topics requiring further analysis

1. Given that land rise in future, at the time a release to the biosphere may occur, cannot necessarily be assumed to be the same as that at present, it would therefore be interesting to explore whether a reasonable variation in the rate of land rise would have a significant impact on the calculated LDF for key radionuclides.

2. It would be instructive to examine in more detail the sensitivity of calculated LDFs to a reasonable variation in irrigation rate, especially under the assumption that such water might be drawn from underground sources.

3. It would be instructive to examine the potential sensitivity of calculated LDFs (or, more specifically, calculated concentrations in agricultural soils) to possible alternative conceptual assumptions regarding how peat becomes contaminated prior to a wetland being drained.

4. It would be valuable to consider whether the precise discharge location within a defined biosphere object is likely to have a significant influence on the subsequent transport and accumulation of radionuclides within the biosphere, as well as estimates of radiological exposure to members of the local community.

5. It may be helpful to explore credible potential exposure pathways that are more ‘exotic’ (e.g. relating to the use of peat as a fuel) but nevertheless broadly consistent with present-day or recent historical human activities.

Topics requiring additional competence

1. None identified.

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The Swedish Radiation Safety Authority has a comprehensive responsibility to ensure that society is safe from the effects of radiation. The Authority works to achieve radiation safety in a number of areas: nuclear power, medical care as well as commercial products and services. The Authority also works to achieve protection from natural radiation and to increase the level of radiation safety internationally.

The Swedish Radiation Safety Authority works proactively and preventively to protect people and the environment from the harmful effects of radiation, now and in the future. The Authority issues regulations and supervises compliance, while also supporting research, providing training and information, and issuing advice. Often, activities involving radiation require licences issued by the Authority. The Swedish Radiation Safety Authority maintains emergency preparedness around the clock with the aim of limiting the aftermath of radiation accidents and the unintentional spreading of radioactive substances. The Authority participates in international co-operation in order to promote radiation safety and finances projects aiming to raise the level of radiation safety in certain Eastern European countries.

The Authority reports to the Ministry of the Environment and has around 270 employees with competencies in the fields of engineering, natural and behavioural sciences, law, economics and communications. We have received quality, environmental and working environment certification.

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